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Luís Bragança · Katerina Tsikaloudaki · Christina Giarma · Ricardo Mateus · Karolos Kontoleon · Rand Askar · Adriana Salles · Camila Cervantes *Editors*

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Proceedings of ReSBE 2026 International Conference - Volume 1

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Editors

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Springer

Editors
Luís Bragança
Department of Civil Engineering
University of Minho
Guimarães, Portugal

Christina Giarma
School of Civil Engineering
Aristotle University of Thessaloniki
Thessaloniki, Greece

Karolos Kontoleon
School of Civil Engineering
Aristotle University of Thessaloniki
Thessaloniki, Greece

Adriana Salles
ISISE
University of Minho
Guimarães, Portugal

Katerina Tsikaloudaki
School of Civil Engineering
Aristotle University of Thessaloniki
Thessaloniki, Greece

Ricardo Mateus
Department of Civil Engineering
University of Minho
Guimarães, Portugal

Rand Askar
ISISE
University of Minho
Guimarães, Portugal

Camila Cervantes
ISISE
University of Minho
Guimarães, Portugal



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Preface

As Organisers of ReSBE 2026, we are honoured to present the Proceedings of the International Conference *ReShaping the Built Environment through Sustainability and Circularity*, held in Thessaloniki, Greece, from the 20th to the 23rd of October 2026.

Published in Open Access by Springer, these Proceedings reflect our commitment to making research and practical innovation at the intersection of sustainability, circularity, and the built environment widely available. By ensuring that the contributions can be consulted, cited and applied without restrictions, we hope to support informed decisions and accelerate positive change in the built environment and in society as a whole.

Society and governments require a more efficient, resilient, and regenerative built environment. Buildings and infrastructure shape patterns of resource use, energy demand, carbon emissions, social well-being, and economic development. In this context, the Circular Economy offers a vital framework for decoupling value creation from the consumption of finite resources by extending the service life of products and materials, enabling reuse and recovery, and promoting the valorisation of by-products and waste. Construction and the built environment have therefore become priority areas for policy, research, and professional practice, including within the European Commission's Circular Economy Action Plan. In parallel, the implementation of sustainability principles into the various scales of the built environment remains a primary goal of numerous policies and scientific efforts worldwide. ReSBE 2026 responds to this complex agenda by moving beyond incremental improvement and by advancing transformative approaches that drive systemic change across the design, construction, operation, and renewal of the built environment.

The conference was organised by the Laboratory of Building Construction and Building Physics of the School of Civil Engineering, Aristotle University of Thessaloniki, and the Department of Civil Engineering of the University of Minho, in collaboration with the COST Action CA21103 "Implementation of Circular Economy in the Built Environment – CircularB", with the support of the International Initiative for a Sustainable Built Environment (iiSBE).

ReSBE 2026 also marked an important moment in the journey of COST Action CircularB. Alongside presenting cutting-edge research, the conference provided an opportunity to showcase the Action's achievements, disseminate its results, and celebrate the collective efforts of its international network in advancing circularity in the built environment. More importantly, it created a platform for engaging the wider scientific, professional, and policy communities, fostering new collaborations and extending the impact of CircularB beyond the lifetime of the Action.

Within the ReSBE 2026 programme, the 1SBE event "Sustainability in the Built Environment Supported by Circular Strategies: Theory Meets Practice" further strengthened the conference's international scope. As part of the SBE Conference Series, this event created a forum for dialogue among policymakers, industry representatives, social

partners, and academics, thereby linking scientific knowledge with implementation challenges and opportunities.

ReSBE 2026 was devoted to presenting recent scientific advances, showcasing practical applications that bridge academia and industry, and discussing key issues concerning the contribution of sustainability and circularity to the modern and future built environment, its construction, and its infrastructure. A principal goal of the conference was to foster the exchange of ideas, methods, and evidence in ways that inspired innovative research paths and advanced new collaborative endeavours across disciplines, geographies, and sectors.

The conference received 541 abstracts from 1368 authors across 71 countries. Following a rigorous peer-review process, 335 full scientific papers were accepted for publication and organised into twelve thematic sections:

1. *Circular Design and Construction:* design for adaptability, reuse, and disassembly; material passports; modularity and standardisation.
2. *Sustainable Buildings, Infrastructures and Cities:* sustainability assessment frameworks, sustainable design, construction, operation and management; synergies across scales.
3. *Lifecycle Assessment, Metrics and Monitoring:* whole-life carbon, embodied energy, circularity indicators, benchmarking frameworks, multi-criteria decision-support methods, and AI/IoT-enabled lifecycle monitoring.
4. *Digitalisation and Automation:* BIM-based approaches, digital twins, digital passports, AI-powered tools, and decision-support systems.
5. *Climate Adaptation and Resilience:* climate-responsive design, resilient infrastructure, and nature-based solutions.
6. *Energy and Performance:* net-zero energy, carbon-neutral buildings, renewable energy integration, and smart grids.
7. *Materials and Innovation:* bio-based and regenerative materials, advanced composites, and secondary raw materials through industrial symbiosis.
8. *Urban and Regional Perspectives:* circular cities, heritage regeneration, and urban mining.
9. *Financing and Market Transformation:* circular business models, green financing, and innovative procurement strategies.
10. *Policy and Governance:* regulatory frameworks, certification systems, and leadership for circularity.
11. *Stakeholders and Collaboration Models:* roles, interactions, and governance mechanisms for systemic change.
12. *Societal and Educational Dimensions:* awareness, equity, skills, and capacity-building for sustainable transitions.

The contributions in these proceedings offer readers a broad and timely overview of the concepts, tools, technologies, policies, and case studies that are shaping the transition towards a sustainable and circular built environment. They address questions of direct relevance to researchers, designers, engineers, architects, policymakers, educators, and industry stakeholders, from whole-life performance and digitalisation to financing models, governance frameworks, stakeholder collaboration, and capacity-building.

Taken together, these contributions demonstrate that innovation, circularity, and sustainability are deeply interconnected. They also show that progress depends not only on technical solutions, but also on new forms of cooperation, new metrics for value and performance, and a shared willingness to rethink established practices. In light of this, the present Open Access publication aims to be a collection of high-quality research and serve as a catalyst for further inquiry, dialogue, collaboration and action.

We extend our deepest gratitude to all authors, the members of the Scientific Committee, the reviewers whose careful work upheld the excellence of the selected articles, and our publishing partners for their invaluable support. May these Proceedings inspire and facilitate the ongoing effort to engineer a sustainable, circular, and regenerative built environment for all.

The Organising Committee,

Luís Bragança
Katerina Tsikaloudaki
Christina Giarma
Ricardo Mateus
Karolos Kontoleon
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Circular Design and Construction: Design for Adaptability, Reuse, and Disassembly; Material Passports; Modularity and Standardisation

Revitalizing Cultural Heritage Through Passive Design Strategies: The Case of Vernacular Houses in Sredačka Župa

Mirjana Miletić(✉) and Nebojša Gadžić

Architecture, Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, 38220 Kosovska Mitrovica, Serbia
mirjana.miletic@pr.ac.rs

Abstract. Cultural heritage buildings embody centuries of climate-responsive knowledge and provide valuable insights for addressing contemporary sustainability and circularity challenges. This paper investigates the vernacular residential architecture of a settlement in Kosovo, characterized by compact dwelling forms and masonry construction, in order to examine how traditional passive design strategies can inform regenerative and circular renovation approaches. The study combines field-based morphological analysis with digital environmental simulations conducted in DesignBuilder. The typical Sredačka Župa house, defined by thick stone walls, timber upper floors, deep eaves, internal courtyards, and small, strategically oriented openings, reveals a coherent system of passive climate control. These features contribute to high thermal mass, effective seasonal shading, favorable surface-to-volume ratios, and microclimatic regulation through semi-open transitional spaces. A representative dwelling was modeled to assess environmental performance under current climatic conditions. The results indicate that the pronounced thermal inertia of the traditional construction system plays a significant role in stabilizing indoor thermal behaviour. Furthermore, minimal and reversible interventions, including selective interior insulation, improved airtightness, and optimized shading strategies, demonstrate measurable reductions in heating energy demand of up to 22% without compromising architectural authenticity. The findings highlight vernacular architecture as an inherently circular system and emphasize its potential to support energy-efficient adaptive reuse and regenerative renovation strategies.

Keywords: Vernacular Architecture · Passive Design Strategies · Design Builder Simulations · Circular and Regenerative Design

1 Introduction

Climate change has intensified the need for more sustainable and resource-efficient approaches in the building sector, which remains one of the largest consumers of energy and materials worldwide. Contemporary architectural discourse increasingly acknowledges that technological solutions alone cannot adequately address environmental challenges without integrating accumulated spatial and climatic knowledge. In this context,

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cultural heritage buildings represent a valuable repository of climate-responsive intelligence developed through centuries of empirical adaptation. Vernacular architecture, in particular, embodies construction principles that inherently integrate environmental, material, and functional efficiency. These traditional systems frequently demonstrate sophisticated passive strategies capable of minimizing energy demand while ensuring adequate indoor comfort [1–3].

The houses of Sredačka Župa represent a compelling example of such architecture, characterized by compact volumetric forms, massive stone walls, timber structural systems, and carefully articulated semi-open transitional spaces. These architectural features indicate the presence of a coherent system of passive environmental control embedded within traditional design logic [4, 5]. The environmental implications of these systems require systematic validation through contemporary analytical tools. Therefore, this study investigates the vernacular residential architecture of Sredačka Župa through an integrated morphological and simulation-based approach.

The research is guided by the following central question:

RQ: *How do traditional passive design strategies and construction systems influence the environmental performance of vernacular houses, and to what extent can minimal, reversible interventions improve their energy efficiency?*

2 Theoretical Background

Vernacular architecture represents a cumulative body of knowledge shaped through long-term adaptation to local climatic, material, and socio-cultural conditions. Traditional dwellings typically rely on passive environmental strategies embedded within their spatial organization, materialization, and construction systems [6]. These strategies commonly include high thermal mass, compact building forms, controlled openings, and semi-open transitional spaces, all contributing to thermal regulation and indoor comfort. Previous research indicates that such principles can significantly enhance environmental responsiveness while reducing energy demand [7].

Vernacular structures often exhibit inherently circular characteristics, including the use of local materials, low-energy construction techniques and long service life [8].

However, the environmental performance of vernacular houses requires systematic validation through quantitative approaches. Building performance simulation provides a reliable framework for assessing thermal behavior, energy demand, and the effects of minimal, reversible renovation strategies. This study builds upon these theoretical perspectives by examining vernacular residential architecture through the integrated lens of passive design, sustainability, and circular renovation [9, 10].

3 Case Study

The research investigates the vernacular residential architecture of **Sredačka Župa**, Kosovo, a rural mountainous region distinguished by its compact settlement morphology and long-standing continuity of traditional construction practices (see Fig. 1). The built environment of this area reflects a close relationship between architecture, climate, and locally available resources, resulting in highly adapted dwelling typologies.

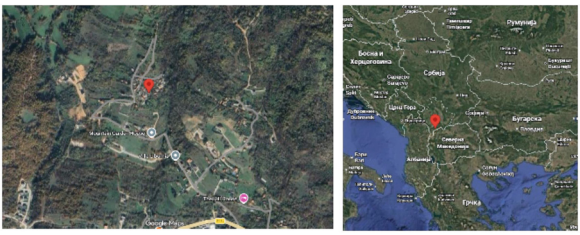


Fig. 1. Geographic position of the analyzed vernacular house in Sredačka Župa (source: Google Maps).

Traditional house in Sredačka Župa is characterized by **compact volumetric forms,** which minimize heat loss and optimize the surface-to-volume ratio. The structural system is primarily defined by **massive stone perimeter walls**, typically ranging from **60 to 80 cm in thickness**, providing both structural stability and significant thermal mass. Stone masonry, commonly bonded with mud mortar, represents a dominant construction technique rooted in local material availability and craftsmanship traditions (see Fig. 2).



Fig. 2. Floor plan and vertical section of the representative vernacular house (left) and exterior view of the dwelling (right) (source: author).

The internal organization of these houses frequently incorporates transitional spatial elements such as the **čardak** and **pretkuća,** which function as semi-open buffer zones. These spaces play a crucial environmental role by moderating thermal exchanges, enhancing natural ventilation, and providing seasonal adaptability. The building envelope is further defined by **small, strategically positioned openings**, deep roof eaves, and a hipped roof configuration, all contributing to solar control and protection from climatic exposure.

In addition to masonry elements, the construction system integrates **timber structural components**, particularly in inter-floor assemblies and internal partition walls. This hybrid system combines the thermal advantages of stone with the flexibility, reparability, and reduced material intensity of timber. Such architectural features indicate the presence of a coherent system of **passive environmental control**, making these dwellings particularly suitable for evaluating climatic responsiveness and circular renovation potential. Based on typological representativeness and preservation of original architectural characteristics, a typical Sredačka Župa house was selected for detailed analysis and simulation modeling [5].

4 Methodology

The study employs an integrated methodological framework combining **morphological analysis** and **building performance simulation**. The initial phase involved field-based architectural investigation of traditional houses in Sredačka Župa, focusing on spatial organization, construction systems, materialization, and passive environmental strategies. Key parameters influencing environmental performance, including wall composition, envelope characteristics, and opening configurations, were systematically documented to define a representative dwelling model [11].

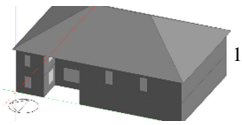
Based on typological representativeness, a typical house was digitally reconstructed using **DesignBuilder**, version 5.03.007. The baseline model reflected the original construction properties and regional climatic conditions. To evaluate renovation potential within conservation-sensitive costraints, several **minimal and reversible intervention scenarios** were tested, including selective interior insulation, improved airtightness, and shading optimization. Environmental performance was assessed through comparative analysis of heating energy demand and thermal behavior across baseline and intervention models [12]. Standard residential occupancy profiles, internal gains, infiltration rates and regional weather data were applied in DesignBuilder. Model validation was performed through comparison with documented thermal characteristics of vernacular buildings in the Balkan region.

5 Simulation Analysis

5.1 Baseline Model

A representative vernacular house was reconstructed in DesignBuilder using the EnergyPlus simulation engine (see Fig. in Table 1.). The baseline model reflects the original construction characteristics typical of traditional Sredačka Župa houses, including massive stone walls, timber structural elements, compact volumetric form, and small window openings. External walls were modelled as thick stone masonry assemblies (approximately 0.70 m), capturing the high thermal mass that dominates the envelope's thermal behaviour. The roof and floor structures were defined according to documented vernacular construction systems. Simulations were conducted using climatic data representative of regional continental conditions with standardized occupancy assumptions. Results indicate that the baseline model exhibits stable thermal behaviour despite the absence of modern insulation. The substantial thermal inertia of stone walls moderates heat transfer and reduces temperature fluctuations. Although heating demand remains relatively high, the envelope demonstrates inherent passive performance advantages (Table 1).

Table 1. Thermal Properties and Envelope Characteristics of the Baseline Model

Element	Description	Thermal Properties	
External Walls	Stone Thickness: **0.70 m**	Conductivity: **1.7–2.2 W/mK** Density: **2200–2400 kg/m^3** Specific heat: **800–900 J/kgK**	 1
Roof	Timber structure with metal sheet covering	U-value **~2.5–3.0 W/m^{2}K**	
Floor	Rammed earth / stone assembly	U-value: **~1.5–2.0 W/m^{2}K**	
Windows	Small openings, single glazing	U-value: **~5.0–5.8 W/m^{2}K**	

[1] *DesignBuilder model of the house*

5.2 Intervention Scenarios

To evaluate energy improvement potential within conservation-sensitive constraints, minimal and reversible interventions were examined. The first scenario introduced selective interior insulation (rock wool of 5 cm thickness), significantly reducing conductive heat losses while preserving the external architectural character.

Comparative simulations reveal a reduction in heating energy demand of approximately **22%,** confirming the effectiveness of low-impact strategies. Improved airtightness further enhanced performance, highlighting infiltration as a major source of heat loss. Optimized shading produced moderate but consistent improvements in seasonal thermal response.

The second scenario examined the impact of reduced infiltration rates through improved airtightness measures, addressing one of the primary sources of heat loss in traditional dwellings. The intervention included improved sealing of window and door junctions and reduction of uncontrolled air leakage while preserving the original architectural appearance. The simulation results indicate a noticeable decrease in heating energy demand, confirming that uncontrolled air leakage significantly affects the thermal performance of vernacular houses. The reduction of infiltration rates resulted in an additional decrease in heating energy demand of approximately **12%,** confirming the significance of uncontrolled air leakage in traditional buildings.

The third scenario evaluated the influence of optimized solar control strategies, including adjustments to shading elements and the functional role of extended eaves. The results reveal moderate yet consistent improvements in thermal behaviour, particularly in transitional and warmer periods, demonstrating the relevance of passive solar regulation. Optimized shading strategies produced a moderate reduction in heating demand of approximately 5%, while contributing to improved seasonal thermal regulation.

5.3 Comparative Performance Assessment

The comparative analysis demonstrates that vernacular houses possess inherent passive advantages that can be effectively enhanced through minimal interventions. The baseline annual heating demand of the representative dwelling was approximately 36 MWh/a. The introduction of selective interior insulation reduced heating demand by approximately 22%, while airtightness improvements contributed an additional reduction of around 11–12%. Optimized shading strategies produced smaller but measurable improvements of approximately 5%, particularly during transitional seasonal periods. These comparative indicators confirm the effectiveness of low-impact passive retrofit strategies in improving the environmental performance of vernacular architecture. The results emphasize the critical role of thermal mass in regulating the environmental behaviour of traditional dwellings. Massive stone walls act as dynamic thermal regulators, while reversible renovation strategies enable measurable efficiency gains without compromising architectural authenticity. These findings support the interpretation of vernacular architecture as an environmentally responsive and inherently circular system (see Table 2).

Table 2. Comparative Performance Assessment

Model Scenario	Envelope Characteristics	Energy Demand Improvement ($kWh/m^2/year$)	Interpretation
Baseline Model	Walls: Thick stone masonry (70 cm) Roof: Timber structure with metal sheet covering Floor: Ground-contact assembly	36 MWh/a	Stable thermal behaviour due to high thermal mass
Scenario 1	Walls: Selective interior insulation applied (Rock wool 5 cm) from 2.0 W/m^2K to 0.6–0.8 W/m^2K	≈22%	Significant reduction of conductive heat losses
Scenario 2	Air exchange: Reduced infiltration (improved airtightness) 1.0–1.5 ACH	≈11% 0.5 ACH	Decrease in infiltration
Scenario 3	Solar control: Optimized shading strategies	≈ 5%	Improvement in seasonal thermal regulation

6 Discussion

The results provide a clear response to the central research question by confirming that the environmental performance of the Sredačka Župa house is fundamentally shaped by its traditional construction logic. The massive stone masonry walls, through their

high thermal mass, generate pronounced thermal inertia, moderating heat transfer and stabilizing indoor temperature variations. Although the baseline model indicates relatively high heating demand, the stable thermal behaviour reveals inherent passive advantages embedded in the compact form, controlled openings, and transitional semi-open spaces. The analysis further demonstrates that minimal and reversible interventions can significantly improve energy efficiency. Selective interior insulation produced the greatest reduction in heating demand (≈22%), while improved airtightness achieved an additional decrease (≈11%), highlighting infiltration as a critical factor. Optimized shading strategies generated moderate but consistent improvements (≈5%), reinforcing the role of passive solar control. Collectively, these findings confirm that traditional passive design strategies play a decisive role in environmental performance and that conservation-sensitive interventions can enhance efficiency without compromising architectural authenticity. Vernacular houses thus emerge as environmentally responsive and inherently circular systems, demonstrating strong compatibility with contemporary sustainability and regenerative renovation principles. However, the study is based on a single representative case study and adopts a strongly place-based methodological approach focused on the specific climatic, material, and morphological characteristics of Sredačka Župa. Therefore, the findings cannot be universally generalized to all vernacular contexts. Nevertheless, the research contributes to the broader discourse on sustainable heritage renovation by demonstrating how passive environmental strategies embedded in traditional architecture can support contemporary circular and regenerative design approaches. The study also provides a transferable methodological framework that may inform future investigations of vernacular settlements in comparable climatic and cultural contexts.

7 Conclusion

This study demonstrates that the vernacular residential architecture of Sredačka Župa possesses significant passive environmental performance potential. The simulation results confirm that traditional construction systems, particularly massive stone masonry walls, play a decisive role in thermal regulation through pronounced thermal inertia. Despite the relatively high heating demand observed in the baseline model, the stable thermal behaviour indicates that these buildings inherently embody climate-responsive design principles.

The analysis further reveals that minimal and reversible interventions can achieve substantial improvements in energy efficiency. Selective interior insulation, improved airtightness, and optimized shading strategies collectively demonstrate that energy optimization can be pursued without compromising architectural authenticity. These findings highlight the compatibility between heritage preservation objectives and contemporary sustainability requirements.

Beyond energy performance, the research reinforces the interpretation of vernacular houses as inherently circular systems. Their reliance on durable local materials, long service life, reparability, and passive climatic adaptation aligns closely with circular economy and regenerative design principles. Rather than representing obsolete construction models, vernacular dwellings demonstrate a latent capacity for environmental optimization and adaptive reuse.

Although the research is limited to a specific vernacular context, its broader contribution lies in illustrating the potential of integrating traditional passive design knowledge into contemporary energy-efficient adaptive reuse strategies. The findings emphasize the relevance of vernacular architecture as a source of climate-responsive and circular design principles that may inspire conservation-sensitive renovation practices in other regions with similar environmental conditions.

The study therefore underscores the importance of integrating heritage-based architectural knowledge into contemporary renovation practices. Traditional buildings should be recognized not only as cultural assets but also as valuable resources for developing resilient, low-impact, and energy-efficient architectural strategies.

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NETRACCI: Operationalising Circular Governance in the Built Environment

Niclas Ihren and Moa Turander(✉)

Matters Group, Stockholm, Sweden
moa@mattersgroup.com

Abstract. The transition to a circular and net-zero built environment requires new governance structures that translate sustainability ambitions into operational decisions across the value chain. This paper presents early findings from the Netracci project, a Swedish multi-stakeholder initiative running 2025–2027 involving 20 industrial partners and 3 research institutions. Based on current-state maturity assessments of real estate companies, architects, and suppliers, the paper identifies actor-specific barriers to circularity. Suppliers face challenges in providing verified lifecycle data spanning circular business models, environmental impact, and total cost of ownership. Architects lack competence in translating circular data into design and business cases. Needs owners exhibit a maturity gap characterised by imbalanced capabilities and a narrow focus on reuse over systemic circular strategies. A novel six-dimensional maturity framework reveals that circular maturity lags significantly behind sustainability maturity among needs owners. Three hypotheses guide the research: (1) regulatory focus on supply-side measures has outpaced customer-side readiness; (2) financial governance centred on initial investment constitutes the primary blockage among needs owners; and (3) insufficient ecosystem dialogue prevents coordinated action. The paper concludes with implications for operationalising circular governance across the value chain.

Keywords: Circular Economy · Built Environment · Governance · Maturity Assessment · Lifecycle Thinking · ISO 59000 · Total Cost of Ownership · Digital Product Passport

1 Introduction

The built environment accounts for approximately 40% of global carbon emissions and half of all extracted materials [1]. Translating high-level sustainability ambitions into operational decisions remains a central challenge [2], and governance structures enabling cross-value-chain collaboration are largely absent. Despite growing regulatory pressure—including the Eco-design Directive and Digital Product Passport requirements—circular practices remain niche rather than mainstream.

The Netracci project (2025–2027) was designed to address this gap. It brings together 20 partners from architecture, construction, interiors, real estate, and digital services, alongside research partners from Matters Group, RISE, KTH, and Linköping University, to develop and test a circular governance framework aligned with ISO 59000. Three hypotheses structure the inquiry:

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H1 – The Supply-Demand Maturity Gap: Regulatory measures have focused on the supply side, creating an asymmetry where suppliers are more ready to deliver circular products than customers are to procure them.
H2 – The Financial Governance Hypothesis: The primary blockage among needs owners lies in financial governance structures that prioritise initial capital expenditure over total cost of ownership (TCO).
H3 – The Ecosystem Dialogue Hypothesis: Insufficient value-chain dialogue prevents the coordinated action needed for circular transition.

This paper reports early findings from Work Package 2 (WP2), which conducted current-state maturity assessments across all participating organisations.

2 Theoretical Framework

2.1 Circular Economy and Barriers to Transition

The circular economy represents a fundamental shift from linear "take-make-waste" models to systems that prioritise resource retention, value recovery, and regenerative design [3], spanning the R-hierarchy from reuse (R3–R4) through remanufacturing to recycling (R8–R9) [4]. The ISO 59000 series provides a standardised framework emphasising systemic thinking, value creation, and stakeholder collaboration [5]. Kirchherr et al. [2] identified cultural, regulatory, financial, and structural barriers in the EU—often interconnected and requiring simultaneous resolution. The present research builds on this by focusing on governance and actor-specific capabilities within the built environment value chain.

2.2 Maturity Assessment as a Governance Tool

Maturity models offer a structured approach to benchmarking organisational capabilities, identifying gaps, and charting improvement pathways [6, 7]. In the context of circular economy, they help organisations understand their position on the linear-to-circular transition and prioritise interventions accordingly.

2.3 The Netracci Circular Management Maturity Model

The project developed a maturity model tailored to real estate companies and major owner-occupiers, structured across six interconnected dimensions: (1) Strategic Leadership & Investment – assessing whether circularity and net-zero are embedded in core business strategy and financial decision-making; (2) Portfolio & Asset Management – evaluating practical application of circular principles across the asset portfolio; (3) Development & Project Management – how circularity is designed into new assets and refurbishments; (4) Data, Technology & Systems – enabling measurement and data-driven decision-making; (5) Ecosystem & Collaboration – engagement with value chain partners, industry peers, and policymakers; (6) Value Proposition & Market Positioning – how circular strategy translates into tangible value for tenants and investors.

Each dimension is assessed against a five-level maturity scale: Level 1 (Ignorance/Linear) – no awareness of circular economy concepts; Level 2 (Ad hoc/Beginner) – isolated projects, no strategic framework; Level 3 (Structured/Developer) – strategy exists, systematic implementation begins; Level 4 (Excellence/Integrated) – circularity is core to the business model; Level 5 (Pioneering/Systemic) – ecosystem shaping and net-positive impacts. A core premise of the framework is that organisations must achieve balanced maturity across all six dimensions to enable effective circular governance.

3 Methodology

Netracci is structured into six work packages; this paper draws on WP2 (Current State Analysis), which assessed circular capabilities across all partner organisations. Assessments were conducted through questionnaire-based self-assessments supported by document analysis of sustainability reports, procurement policies, project briefs, and governance documents (Table 1). For suppliers, additional data collection followed the Integrated Circularity and Sustainability Model framework, capturing corporate capabilities and product-level specifications across environmental, circularity, social, and financial parameters.

Organisations were grouped into three actor categories: needs owners – real estate companies and large tenants (n = 5); architects – firms involved in commercial and residential design (n = 5); and suppliers – manufacturers of products and materials for interiors and construction (n = 7). This categorisation enabled cross-actor comparison and identification of distinct capability profiles, directly supporting investigation of H1.

Table 1. Key documents collected for validation, mapped to assessment dimensions.

Document Type	Primary Validation Area
Corporate/Sustainability Strategy	Strategic Intent
Green Procurement Policy	Supply Chain Governance
Green Investment Framework	Financial Integration
Net Zero/Circularity Roadmap	Portfolio-Wide Execution
Standard Project Brief Template	Project-Level Governance
Life Cycle Assessment (LCA) Report	Data Use in Design
Annual Sustainability Report	Transparency & Communication
Green Lease / Tenant Fit-out Guide	Tenant Collaboration
Circular Partnership Agreement (MoU)	Ecosystem Collaboration
Evidence of Green Financing	Market Credibility & KPIs

4 Findings

4.1 H1: The Supply-Demand Maturity Gap

Maturity assessments revealed a pattern consistent with H1. Suppliers demonstrated moderate-to-high willingness to deliver circular products; however, their ability to provide verified data across circular business models, environmental lifecycle data, and TCO financial parameters was uneven. Critically, needs owners' readiness to procure circular solutions lagged significantly behind supplier willingness to provide them (Table 2).

Table 2. Supplier circular readiness indicators.

Indicator	Average Score / Response
Circular business model existence	70% have developed some circular offering
Circular offer coverage (% of portfolio)	<30% average
EPD/LCA capability	60% have in-house or external capability
Buy-back/take-back system in place	40% have operational systems
Digital Product Passport roadmap	25% have a concrete timeline
Circular project references	Limited to pilot scale in most cases

> We have circular products ready to go. We have take-back systems. We have refurbishment capabilities. But our customers aren't asking for them, and when they do, they don't have the procurement processes or investment models to value what we're offering. – Supplier representative

4.2 H2: The Financial Governance Hypothesis

All five needs owner organisations showed financial governance structures that consistently favoured initial capital expenditure over lifecycle value. None had mandatory TCO requirements for investment decisions; payback period requirements (typically 3–5 years) conflicted with longer-term circular value realisation; and risk assessment methodologies did not capture risk reductions associated with circular strategies. Procurement remained heavily weighted toward lowest initial price, and circular criteria—where present—were treated as optional.

> *Our investment model is not capable of managing even marginally increased investments, even if that leads to lower TCO. We're measured on project IRR and payback periods. Shifting to TCO is a cultural and financial shift we haven't made yet. – Real estate sustainability manager*

4.3 H3: The Ecosystem Dialogue Hypothesis

The assessment revealed fragmented cross-actor dialogue consistent with H3. Architects lacked a forum to collectively articulate data needs to suppliers; suppliers expressed willingness to develop circular offerings but received unclear market signals; needs owners had circular ambitions but had not communicated these as procurement requirements. No structured mechanisms existed for risk-sharing or circular co-investment.

> *We're all doing what we can within our own spheres. But we're not having the conversations across the table about what's really needed. The questions we need to solve together fall outside the regular procurement dialogue. – Architect representative*

4.4 The Supplier Data Trilemma

Suppliers identified a fundamental barrier: the inability to provide verified data across three categories simultaneously. (1) Circular business model data: take-back systems and product-as-a-service offerings lack standardised documentation, and circular offer coverage (the share of portfolio available with circular commercial terms) averaged below 30%. (2) Environmental lifecycle data: EPDs commonly cover cradle-to-gate (A1–A3) only; data on transport and installation (A4–A5), use stage (B), and end-of-life (C) are frequently absent or based on generic scenarios rather than product-specific information. This prevents accurate whole-life carbon assessment and undermines TCO calculations. (3) TCO financial data: parameters such as expected service life, buy-back percentages, and guarantee coverage risk factors are rarely collected or disclosed.

This data trilemma is a systemic barrier that individual suppliers cannot solve alone—it calls for shared infrastructure and standardised reporting frameworks across the sector.

4.5 Architect Challenges

Architects face a dual challenge. First, they lack competence in interpreting and applying circular product data in design. While trained to optimise for aesthetics and function, integrating circularity metrics into early-stage design is new territory. Second, they are expected to act as advisors translating circular ambitions into financially viable concepts—a shift from initial investment thinking to TCO modelling that is not yet widespread in the profession.

> *We're expected to lead the client into circularity, but we don't have the tools or the training to do it confidently. And even when we get data from suppliers, it's in different formats, different units, and we have no way to compare options systematically. – Architect*

4.6 Needs Owner Maturity Profiles

Across all five needs owner organisations, circular maturity (averaging Level 2–3) was consistently and significantly lower than sustainability maturity (Level 3–4). This reflects

the relative novelty of circular economy as a management concept in real estate. Sustainability has been on corporate agendas for decades, with established metrics, reporting frameworks, and regulatory drivers; circular economy by contrast lacks standardised definitions, mature data infrastructure, and embedded governance mechanisms.

A second pattern was the concentration of circular activity around reuse strategies (R3–R4) rather than more systemic approaches. Many organisations had implemented furniture and fixture reuse pilots, achieving measurable waste reductions. However, engagement with higher-order strategies—design for disassembly (R2), product-as-a-service (R1), or buildings-as-material-banks (R0)—was limited. Beyond the maturity gap, needs owners articulated a critical operational challenge: no systematic mechanism exists to preserve and update product and material data over the asset lifecycle. Digital product passports, where they exist, are not integrated into facility management systems, causing data decay that undermines circular value propositions and prevents buildings from functioning as material banks at end-of-life.

4.7 Cross-Cutting: Data Infrastructure

All actor groups identified fragmented data infrastructure as a major obstacle. Product data, circularity indicators, EPDs, cost parameters, and digital product passports are currently scattered across incompatible systems. Two complementary infrastructure needs were identified: (1) a central credible data repository enabling suppliers to publish verified circular product data once and make it accessible to all authorised procurement processes, reducing transaction costs and improving data quality; and (2) asset lifecycle data management systems for needs owners, integrating BIM, facility management, and digital product passport platforms to track material data over decades and enable eventual material banking when assets are decommissioned.

5 Discussion

5.1 Hypothesis Validation

Preliminary findings provide initial support for all three hypotheses. H1 is supported: the demand-side bottleneck appears significant, though suppliers face their own data challenges. H2 is strongly supported: initial-investment-focused financial governance is the most consistently cited barrier across all needs owner organisations, manifesting in the absence of mandatory TCO requirements, short payback horizons, and procurement processes that systematically exclude lifecycle criteria. H3 is supported: fragmented communication reinforces transactional relationships and prevents the collaborative problem-solving needed for systemic change. The pilot phase of Netracci will provide opportunities to test targeted interventions and to gather longitudinal evidence on each hypothesis.

5.2 From Reuse to Systemic Circularity

The concentration of circular activity around reuse strategies, while valuable, represents an incomplete transition. True circular governance requires engagement with the full R-hierarchy, including design strategies that prevent waste creation (R0–R2) and business

models that retain value at higher levels (R1–R4). This shift demands competence development, new metrics, and willingness to experiment with novel value propositions such as product-as-a-service and design for disassembly. Current efforts anchored in familiar operational improvements—rather than transformative business model innovation—will not alone deliver the systemic change required.

5.3 The Role of Integrated Data Platforms

The Netracci project is developing an integrated data model linking material passports, circular indicators, EPDs, and cost parameters into a BIM-compatible decision-support tool. This addresses the cross-cutting data challenge by enabling supplier capability assessment through corporate maturity scoring; product-level circularity indexing based on R-strategy parameters; environmental impact comparison using standardised EPD modules; and total cost of ownership calculations incorporating service life, warranties, buy-back commitments, and guarantee risk factors. Early pilot planning suggests such tools can reduce the transaction costs of circular procurement and support evidence-based decision-making—but the tool is only as effective as the data it contains, underscoring the need for both complementary data infrastructures identified in Sect. 4.7.

5.4 Actor-Specific Interventions and Emerging Risks

Suppliers require standardised data templates aligned with EN 15804, EN 16810, and ISO 59000, together with access to central data repositories that reduce repeated disclosure burden. Architects need TCO modelling capabilities, circular design guidelines, and access to verified product data through BIM-compatible platforms. Needs owners must build asset lifecycle data infrastructure, broaden their circular focus beyond reuse, reform investment frameworks to capture lifecycle risk reductions, and create governance mechanisms for long-term supplier commitments.

Circular models also introduce new long-term risks alongside risk reductions. Suppliers may be asked to provide take-back commitments for 15 or more years—potentially exceeding their commercial lifespan—requiring governance innovations that extend beyond traditional warranties.

6 Conclusion

This paper has presented early findings from the Netracci project, highlighting actor-specific challenges in operationalising circular governance in the built environment. Suppliers face a data trilemma requiring the simultaneous provision of circular business model data, environmental lifecycle data, and TCO financial parameters—a systemic barrier that exceeds what individual firms can solve alone. Architects lack the competence and tools to integrate circularity metrics into design workflows and business case development. Needs owners exhibit a sustainability-circularity maturity gap, a narrow reuse focus rather than systemic circular strategies, and insufficient data infrastructure to maintain product data across asset lifecycles.

Preliminary evidence supports all three guiding hypotheses: a significant supply-demand maturity asymmetry (H1); financial governance centred on initial expenditure as the primary blockage among needs owners (H2); and fragmented ecosystem dialogue that prevents coordinated action (H3). These findings inform the design of WP5 pilot interventions targeting each hypothesis in commercial real estate settings.

The paper contributes to emerging circular governance literature by demonstrating the need for differentiated actor-specific support, integrated data infrastructures, and new instruments for managing long-term circular commitments. Future work will track longitudinal changes in maturity as pilots progress.

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Advancing Circular Construction Through Digital Product Passports

Angel Jimenez-Aranda(✉) and Juan Antonio Ferriz-Papi

University of Salford, Manchester M5 4WT,, UK
a.jimenez-aranda@salford.ac.uk

Abstract. Digital Product Passports (DPPs) are increasingly recognised as a key enabler of sustainability and circularity in the construction sector, offering a structured way to capture, share, and reuse accurate product information across the entire lifecycle of built assets. By providing transparent data on product performance, provenance, environmental impact and compliance, DPPs support responsible procurement, reduce waste, and create new opportunities for reuse and recycling, which are essential principles for achieving circular construction. In this context, SmartScan, a digital tool developed by the University of Salford, demonstrates how DPP-aligned solutions can be implemented in practice. SmartScan connects product barcodes and QR codes through the Global Trade Item Number to verified manufacturer data, including safety documentation, installation guidance, environmental product declarations, and origin information, providing essential information for users across the construction supply chain. This study investigates how SmartScan can contribute to sustainable construction by improving material traceability and enabling more informed decision-making throughout the product lifecycle. Through user testing and analysis of product data flows, the research shows that SmartScan enhances access to environmental information, supports lower-impact material choices, and strengthens opportunities for circularity in procurement, reuse, and end-of-life processes. The findings highlight the value of tools based on global data standards in promoting sustainable and circular practices and illustrate how manufacturers can organise and share their product data to better support the construction supply chain.

Keywords: Digital Product Passports · Circular Economy · Product Traceability · Sustainability · Smart Construction

1 Introduction

The construction sector, encompassing the planning, design, manufacture, construction, operation, maintenance, and demolition of buildings and infrastructure, is central to sustainability and circular economy goals but remains one of the most resource-intensive and waste-generating industries. Buildings and construction account for about 37% of global energy-related carbon emissions and a large share of material consumption, highlighting the need to improve material efficiency and reduce lifecycle impacts in the built environment [1]. Circular economy strategies are increasingly promoted to address

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these challenges through improved resource efficiency, reuse of building components, and longer product lifetimes [2, 3].

Digital technologies are recognised as key enablers of circular construction. Tools such as Building Information Modelling (BIM), the Internet of Things (IoT), artificial intelligence (AI), and digital product information systems can enhance lifecycle information management and transparency across construction supply chains [4, 5]. They support material traceability, collaboration, and data-driven decision-making across design, procurement, construction, and operation phases [6]. However, adoption remains limited because product and material information is often incomplete, difficult to access, or disconnected from the physical products installed in buildings.

A key barrier is the lack of reliable and interoperable product information across the lifecycle of built assets. Circular decision-making requires knowledge of installed products, including their composition, provenance, environmental performance, and end-of-life options. In practice, this information is fragmented across manufacturer documentation, project systems, and static files, limiting integration with digital tools and disrupting lifecycle information continuity [3, 4]. This fragmentation restricts opportunities for reuse, refurbishment, and recycling of building components [2, 3].

Digital Product Passports (DPPs) have emerged as a promising approach to addressing these information gaps [7–10]. DPPs provide structured digital identities for products containing data on composition, technical characteristics, environmental performance, and end-of-life management. By enabling persistent access to product information, DPPs can improve transparency and traceability across supply chains and support sustainable procurement, maintenance, and material recovery [11].

Policy developments are accelerating DPP adoption. The Ecodesign for Sustainable Products Regulation (ESPR) [12] introduced by the European Commission establishes a framework for digital product passports across multiple product groups. Complementary initiatives, including revisions to the Construction Products Regulation, aim to strengthen digital product information requirements in construction supply chains.

Standardisation efforts for Digital Product Passports (DPPs) are still evolving, with ongoing work across European and international standardisation bodies to define common data structures, interoperability requirements, and sustainability-related information for construction products. In particular, CEN/TC 350/SC1/WG4 is currently working on the definition of product properties with circularity significance that should be integrated into a DPP dataset, supporting greater transparency, traceability, and circular economy practices within the construction sector.

The effectiveness of DPPs depends on global data standards and digital identification mechanisms linking physical products to digital information. Standardised identifiers allow products to be uniquely identified and connected to verified data repositories, improving interoperability and integration with procurement and asset-management systems [13].

Despite increasing attention to DPPs, empirical evidence on operational DPP-aligned tools in construction remains limited. Most research focuses on conceptual frameworks or regulatory aspects rather than practical implementations and their impact on procurement, material selection, reuse, and end-of-life decisions.

This study addresses this gap by examining SmartScan, a digital tool that aligns with DPP principles and links physical construction products with verified manufacturer data through digital identifiers. By connecting product identifiers encapsulated in barcodes and QR codes to product records, SmartScan enables access to safety documentation, installation guidance, environmental product declarations, and provenance information. This research investigates how SmartScan improves material traceability and access to lifecycle-relevant product information.

2 Methodology

This study adopts an exploratory case study approach to investigate how a DPP–aligned digital tool can support sustainable and circular practices in the construction sector. Given the early stage of DPP adoption in construction, an exploratory design enables in-depth analysis of processes, user interactions, and data flows that would be difficult to capture through large-scale quantitative methods.

SmartScan is a digital tool developed by the University of Salford that links physical construction products to verified digital information. At its core, the system connects the Global Trade Item Number (GTIN) encapsulated in barcodes and QR codes with a digital data layer. When a product is scanned, users are directed to aninterface that provides access to manufacturer-verified product information (see Fig. 1).

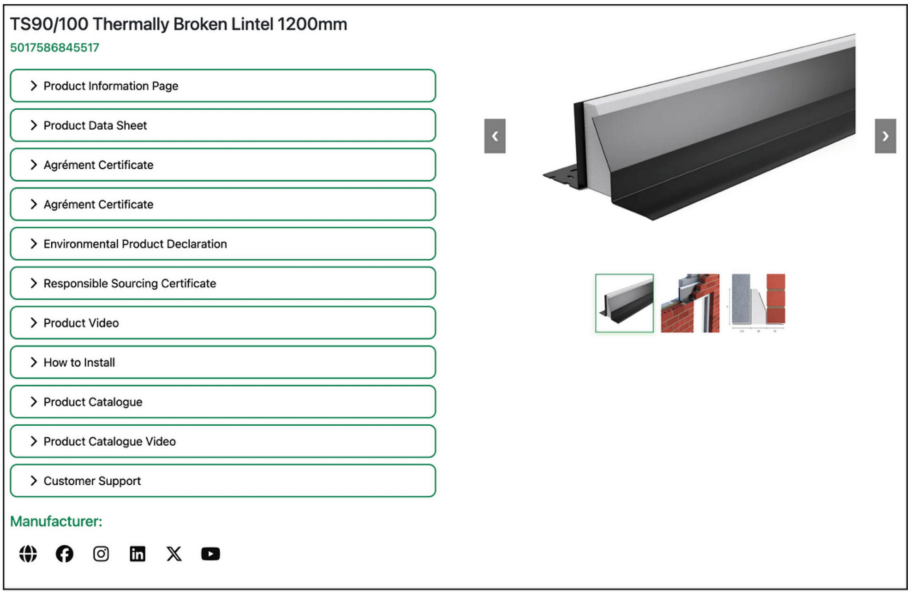


Fig. 1. Screenshot of a product information page in SmartScan

The system architecture is designed to support interoperability and data integrity. Rather than storing all information locally, SmartScan functions as a connector between

physical identifiers and authoritative data sources maintained by manufacturers or trusted platforms. This approach reduces duplication and supports the principle of a single source of truth for product information. The types of data accessible through SmartScan include safety documentation, installation and maintenance guidance, environmental product declarations (EPDs), and provenance information.

SmartScan aligns with key DPP principles by enabling persistent linkage between products and their digital records, supporting multi-stakeholder access to information, and facilitating lifecycle-oriented data use. Although it does not represent a fully standardised DPP as defined in emerging regulations, it operationalises many of the functional requirements associated with DPPs, particularly in relation to traceability, transparency, and lifecycle accessibility.

In the study, data collection focused on two complementary components: user testing and analysis of product data flows. User testing was conducted with participants representing different roles within the construction supply chain who interact with product information at different lifecycle stages. Participants were asked to use SmartScan to access product information in simulated scenarios, such as checking installation requirements, verifying safety documentation, or reviewing environmental performance data. Observations were recorded alongside semi-structured feedback on usability, clarity, and perceived value.

In parallel, the study analysed how product data flows through the SmartScan system, mapping the key information categories accessible through the platform against lifecycle stages aligned with ISO 19650 principles. This involved examining the types of data made available, how they are structured, and how they are accessed at different points in the lifecycle. This analysis enabled assessment of both the technical capabilities of the tool and its relevance to sustainability-oriented decision-making.

3 Results

3.1 User Testing

User testing was conducted to assess the effectiveness, usability, and user satisfaction associated with the SmartScan digital platform. The evaluation aimed to simulate realistic usage scenarios and to identify design considerations, usability barriers, and opportunities for system improvement. Insights obtained from this process informed iterative refinements to the digital solution.

To measure user satisfaction, the Post-Study System Usability Questionnaire (PSSUQ) [14] was administered after participants completed a predefined set of tasks. The testing environment included both laptops and smartphones, connected to a smart screen that enabled monitoring of user interactions during task execution. Ethical approval for the usability study was obtained prior to testing, and all participants provided informed consent.

A total of 14 participants took part in the evaluation. Participants completed ten tasks, equally divided between laptop-based and smartphone-based interactions, allowing the research team to assess usability across different device contexts. Data were collected on task completion processes, user responses, and observed interaction patterns, enabling the identification of usability issues and user preferences.

User satisfaction was evaluated using four PSSUQ dimensions. System usefulness (SYSUSE) recorded score of 1.61 ± 0.74, suggesting that users perceived the platform as highly effective for locating and accessing product information. Information quality (INFOQUAL) scored 1.62 ± 0.57, indicating that the content provided by the system was clear, relevant, and aligned with user expectations. Interface quality (INTERQUAL) achieved a mean score of 1.61 ± 0.85, reflecting positive perceptions of the system interface and interaction design. The overall satisfaction score (OVERALL) of 1.60 ± 0.58 indicates a consistently positive user experience across the evaluated tasks. Taken together, these results demonstrate that the SmartScan platform performs strongly in terms of usability and user acceptance.

In addition to the questionnaire results, qualitative feedback was collected during the testing sessions. Overall, the feedback confirmed that users found the platform useful, accessible, and visually well designed, particularly appreciating the ability to reduce time required to locate and access relevant product information. Some challenges related to product comparison and barcode scanning were also identified, helping to inform further improvements to the platform's design and usability.

3.2 Product Data Flow and Lifecycle Information Availability

To evaluate the capability of SmartScan in supporting lifecycle information management, the product data made available through the system was analysed in comparison with principles defined in ISO 19650, the international standard for the organisation and digitisation of information about buildings and civil engineering works using Building Information Modelling (BIM). ISO 19650 establishes that structured information should be produced, managed, and exchanged consistently throughout the lifecycle of built assets to support decision-making, regulatory compliance, and operational efficiency. While ISO 19650 does not explicitly define discrete lifecycle phases, it provides a framework for managing information across the delivery phase, which encompasses design and construction, and the operational phase, covering asset management, maintenance, and end-of-life activities.

To contextualise SmartScan's product data flows, Table 1 was developed that maps the key information categories accessible through the platform against lifecycle stages aligned with ISO 19650 principles. These stages include concept/pre-design, design, procurement, construction/installation, operation/maintenance, and end-of-life /deconstruction.

The analysis highlights that SmartScan delivers structured, accessible information corresponding to the needs of each lifecycle stage. During the delivery phase, the platform supports sustainable material selection, regulatory compliance, and supplier verification by providing access to EPDs, technical specifications, and certifications. During the operational phase, SmartScan maintains access to installation instructions, maintenance guidance, warranties, and provenance information, supporting asset management and enabling circular construction practices such as refurbishment, reuse, and responsible deconstruction.

Overall, the adapted table demonstrates that SmartScan can bridge critical information gaps across the construction lifecycle, enabling traceability, continuity of information, and sustainability-oriented decision-making. By systematically linking physical products to verified digital records, SmartScan illustrates how DPP principles can be operationalised in practice while remaining consistent with ISO 19650 information management frameworks.

Table 1. SmartScan product data mapped to lifecycle stages.

Lifecycle Phase	Typical Information Required	Relevance to SmartScan
Concept / Pre-design (Delivery)	Sustainability targets, project requirements, high-level material performance data, environmental objectives, embodied carbon targets	Provides EPDs and material composition for early sustainability decisions
Design (Delivery)	Product specifications, environmental performance metrics, compliance documentation, certifications, dimensional and technical data	Supports product selection and integration of verified environmental data
Procurement (Delivery)	Supplier information, product certifications, logistics requirements, pricing data, installation prerequisites	Consolidates manufacturer data and certifications for procurement
Construction / Installation (Delivery)	Installation guidance, safety documentation, on-site handling instructions, product identification (QR/Barcode), delivery and logistics records	Links products to installation and safety documents
Operation / Maintenance (Operational)	Maintenance schedules, warranties, asset registers, performance records, service manuals	Maintains access to installation and maintenance information
End-of-life / Deconstruction (Operational)	Product composition, recyclability data, origin/manufacturer information, potential for reuse or remanufacturing	Enables traceability and supports reuse or recycling decisions

3.3 Implications for Sustainability and Circular Construction

The analysis of SmartScan demonstrates clear implications for promoting sustainable and circular practices within the construction sector. By providing structured, accessible product data, the platform supports more informed decision-making throughout the asset

lifecycle, particularly in areas critical to reducing environmental impact and enhancing material circularity. Access to EPDs and technical specifications allows designers and procurement teams to compare materials based on embodied carbon, recyclability, and compliance, facilitating low-impact material selection.

During the operational phase, the platform's availability of maintenance, provenance, and manufacturer data helps facility managers and contractors plan for efficient repairs, refurbishment, or component replacement, extending asset lifespans and reducing unnecessary waste. At the end-of-life stage, provenance and product composition data enable deconstruction teams to identify materials suitable for reuse or high-value recycling, supporting circular construction principles.

SmartScan also illustrates how digital product identification and global data standards can bridge information gaps that typically hinder sustainability initiatives. By linking physical products to verified digital records, the platform ensures that environmental and compliance information remains accessible and trustworthy, mitigating the risk of data loss across project handovers or organizational transitions.

Overall, these capabilities suggest that operational DPP–aligned tools like SmartScan can enhance traceability, reduce material waste, and strengthen the practical implementation of circular strategies, providing measurable support for sustainability objectives across construction projects.

4 Conclusions

This study investigated the usability and functionality of SmartScan, a digital tool designed to align with DPP principles and support sustainability and circularity in the construction sector. Through user testing and product data flow analysis, the research provides empirical insights into how a solution aligned with DPP application can enhance access to product information and inform decision-making across the building lifecycle.

The findings demonstrate that SmartScan enables stakeholders to retrieve relevant information throughout the product lifecycle, from procurement and installation to operation and end-of-life management.

SmartScan also supports sustainability and circular construction practices by improving traceability and enabling evidence-based decision-making. The system allows users to compare products, select lower-impact options, and plan for reuse, refurbishment, and responsible end-of-life management. By linking products to verifiable information, the system reduces data fragmentation and strengthens transparency and trust across construction supply chains. These results illustrate how global data standards and digital identification mechanisms, such as GTINs, can underpin interoperable, lifecycle-oriented product data management.

The practical implications of this study suggest that manufacturers, designers, contractors, and facility managers can adopt DPP-aligned tools like SmartScan to streamline access to product information, support compliance verification, and enhance circularity in building projects. From a policy perspective, these findings reinforce the importance of regulatory initiatives, including the Ecodesign for Sustainable Products Regulation and the Construction Product Regulations, which encourage digitalisation and standardisation of product data to promote sustainable construction practices.

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Restoration of a Building Damaged by an Airstrike with the Reuse of Its Parts: Case Study

Volodymyr Semko[1(✉)], Serhii Skliarenko[2], Anton Makhinko[2], and Nataliia Mahas[3(✉)]

[1] Poznan University of Technology, Poznan 61-138, Poland
volodymyr.semko@put.poznan.pl
[2] State University "Kyiv Aviation Institute", Kyiv 03058, Ukraine
[3] Slovak University of Technology in Bratislava, Bratislava 810 05, Slovakia
nataliia.mahas@stuba.sk

Abstract. The article presents a case study on restoring an industrial building damaged by a missile strike during the armed aggression against Ukraine. The study shows how using existing structural elements in reconstruction can reduce costs, shorten schedules, and minimise environmental impact. The methodology includes assessing the building's life-cycle stages (design, construction, and operation) and analysing missile-strike damage to inform the restoration project. Visual inspections and instrumental measurements determined the building's technical condition and residual deformations. A restoration project was developed based on this data. The project retained the lower parts of the columns, their foundation nodes, foundations, plinth walls, and concrete floor. Damaged steel frames and cladding structures were replaced. Reusing the foundations, plinth walls, and concrete floor lowers construction costs and time, reduces construction waste (about 900 tons of concrete), and decreases embodied energy and CO_2 emissions (GWP $\approx$ 75,000 kg CO_2-eq and PENRT $\approx$ 640,000 MJ) compared to total demolition. The results confirm the technical feasibility and practicality of partial structural reuse in post-war reconstruction, supporting circular economy principles.

Keywords: Building Restoration · Airstrike Damage · Structural Reuse · Steel Frames · Foundations

1 Introduction

In real construction practice, it is extremely rare to encounter cases where a single design and research team can track the entire life cycle of a building – from its design stage to its reconstruction or demolition – as the life cycle of modern buildings ranges from 30 to 100 years, which often equals or exceeds the duration of a person's professional activity. At the same time, emergency situations can shorten a building's life cycle. In such cases, it is rational to involve the original authors of the primary design in the restoration of these buildings, as they are intimately familiar with the building's history.

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The development of specific solutions and comprehensive general methodologies for the restoration of infrastructure destroyed by war must be carried out with significant attention to security [1]. For damage to building envelopes – walls or the infill of window and door openings – researchers are developing solutions for rapid, reliable restoration to return buildings to operational readiness [2, 3]. The main advantage of the technology proposed in [2] lies in its high assembly speed, without the need for heavy, specialised equipment, which is critical in dense urban areas and for the urgent return of buildings to operation. Article [3] conceptualises the term "wartime circularity," and the study demonstrates how urgent needs transform building components (used windows) that were considered waste into a vital resource. Given the scale of destruction and the resulting significant amount of construction waste, the need to transition from a traditional linear consumption model to a circular system that minimises waste and maximises resource efficiency at all stages of the building life cycle is particularly acute [4, 5]. Studies [5, 6] aim to optimise the accounting for and reuse of construction waste generated by war-related destruction in Ukraine.

Given the above, minimising construction waste and the possible reuse of materials, structures, and building components when designing the restoration of damaged objects is an urgent task.

2 Object of Study and Description of its Life Cycle

The object of study is an industrial warehouse building with a storage temperature regime of 0 °C. The building's life cycle (2018–2023) consisted of the following stages:

1. **Feasibility Study, 2018.** The building was designed in accordance with the forecasted indicators of the enterprise's technological needs for storing chilled products. According to the developed concept, a rectangular frame building was designed with two spans (2 × 20 m), overall plan dimensions of 40 × 35 m, and a height of 9.15 m to the bottom of the load-bearing roof structures (Fig. 1, left). Also, at this stage, an attached tiered rack for equipment placement was installed. The dimensions of the rack were 18.0 × 3.5 m. Preliminary solutions included the possibility of constructing an extension for an expedition zone.
2. **Development of the Working Project, 2019.** During the design process, a compromise space-planning solution was achieved by implementing a single-span (32 m) building.

   This led to optimising storage space allocation, reducing construction costs, and introducing variability in technological solutions for rack positioning. The building frame was reduced to dimensions of 32 × 29 m (Fig. 1, right). The use of steel frames with variable cross-sections allowed for a significant reduction in building height. An increase in the metal intensity of the building frame from 45 kg/m^2 (when using open-web trusses with a height of 4.5 m) to 97 kg/m^2 (when using variable cross-section beams with a height from the bottom of the eave node to the ridge of 3 m) proved to be economically feasible, considering the substantial reduction (approximately 1500 m^3) in the refrigerated volume of the warehouse.
3. **Building Construction, 2019–2020.** Construction began in mid-2019. The building was commissioned in the spring of 2020 (Fig. 2, left).

4. **Building Reconstruction, 2020–2021.** During the first season of the building's operation, the optimality of the frame's space-planning solution was confirmed, enabling changes to the layout of product storage systems without redesigning the floor plan. To further optimise technological processes, a reconstruction was designed and completed by the end of 2021 (Fig. 2, right), extending the expedition zone.
5. **Building Operation, 2022–2023.** The warehouse building is conventionally divided into three parts: the warehouse itself, an extension for product dispatch (expedition), and a technological extension for placing engineering equipment (tiered rack). In terms of space planning, the warehouse building was a rectangular frame building with overall plan dimensions of 28.6 × 32.0 m and a height to the bottom of the load-bearing roof structures of 9.3–11.2 m. The size of the tiered rack was 22.5 m × 3.6 m. The expedition zone was rectangular, with overall plan dimensions of 10.0 x 22.5 m and a height to the bottom of the load-bearing roof structures of 4.8 m. Foundations: monolithic reinforced concrete made of class C20/25 concrete on a natural base. The warehouse building frame: a metal frame in the form of a single-span portal. Columns and rafters: variable I-section, welded. Cross-section of main columns: flanges - 350 × 20 mm, webs - 300–950 × 12 mm. Rafters: flanges - 300 × 16 mm, web – 300–580 × 12 mm. The frame's spatial rigidity is ensured by a system of vertical and horizontal bracing. Tiered rack: a separate two-level steel frame. The building floor: 200 mm reinforced concrete of class C20/25 with a "topping" finish and a 50 mm layer of extruded polystyrene thermal insulation. External walls of the warehouse: 160 mm thick wall sandwich panels with a thermal conductivity coefficient of 0.022 W/m × K. Warehouse roof (including expedition): 160 mm thick roof sandwich panels with a thermal conductivity coefficient of 0.022 W/m × K. Doors and gates: metal, thermally insulated.
6. **Emergency Situation and Building Destruction, 2023.** In the autumn of 2023, during the armed aggression against Ukraine, a missile strike was carried out, resulting in significant destruction of the building. Emergency loads on the warehouse structures occurred due to a deflagration explosion of missile fuel inside the building. The blast wave caused additional damage to the main structures from fragments of other structures and the warhead, leading to local weakening of the cross-sections of the building elements. The overall stability of the main warehouse structures at the time of the inspection was maintained; the frame structures did not collapse. The duration of the fire, caused by the combustion of missile fuel residues, did not exceed 15–20 min.
7. **Assessment of the Technical Condition of the Main Building Structures, 2023.** This stage of the life cycle is described in more detail in Sect. 3 of this work.
8. **Project for the Restoration of the Building with the Reuse of Preserved Parts, 2023–2024.** This stage of the life cycle is described in more detail in Sect. 4 of this work.

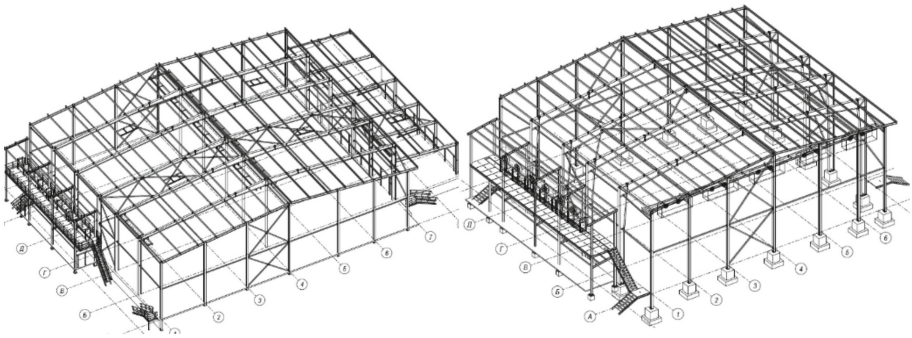


Fig. 1. Preliminary and design solutions for the warehouse building frames.



Fig. 2. Constructed warehouse building with a tiered rack and an attached expedition zone.

3 Description of the Consequences of the Missile Strike and Structural Damage

The epicentre of the explosion was located in the main part of the building. During the explosion in the warehouse section, the wall and roof sandwich panels collapsed, effectively acting as blast-relief structures (even though they were not designed for this type of impact). The blast wave propagated, partially offset on one side by the deformation and displacement of racks filled with products (bulk density of 1–1.5 t/m^3), while on the other side, it created conditions for the directed action of the accidental load on the building structures. Consequently, the load-bearing structures of the tiered rack sustained the greatest impact, leading to excessive deformations, with displacements of its upper part exceeding 600–700 mm.

The warehouse roof and end facades became other directions of the blast wave's targeted impact. The most significant damage was noted in the load-bearing roof structures: general bending and distortion of the rafters, tearing of individual wall or flange sections of the beams, and the tearing away of entire rafter fragments. The roof purlins sustained significant bending (exceeding 1/200 of their length). Approximately 40% of the purlins collapsed. Based on the visual inspection results, the technical condition of the rafters, purlins, vertical and horizontal bracing, and engineering networks was found to be critical (Fig. 3).



Fig. 3. Consequences of the missile strike on the warehouse part of the building.



Fig. 4. Damage to the columns.

Only the foundation structures, the floor, and the fire-fighting water supply networks at the building's entry point were found to be in relatively satisfactory condition, which is explained by the shielding of this area by the monolithic structure of the warehouse plinth wall. To determine the technical condition of the main frame columns and a portion of the gable columns with the aim of maximising their preservation, it was decided to establish the columns' deviations from the vertical and their design positions.

During instrumental measurements, the dimensions of damage to the structural elements were established:

– concrete foundation structures: spalling of the concrete cover layer and protruding parts of the plinth measuring 100 × 100 mm; crack propagation around the columns with lengths of 100–300 mm and opening widths of a = 0.2–5.0 mm; separation of the plinth walls from the floor structure;

– concrete floor structure: spalling of the surface concrete cover layer (impact depth up to 20 mm); punctures in areas where structures fell or fragments penetrated;
– steel frame columns (Fig. 4): overall bending of elements up to 700 mm (for the tiered rack columns), local flange buckling (up to 100 mm), cross-sectional twisting, and through-punctures by fragments (up to 20 mm in diameter);
– steel frame rafters (Fig. 3): damage similar to that of the columns but with significantly larger defect dimensions; approximately 30% of purlins collapsed; torn flanges and webs of the main beams (on 2 frames); and a total absence of a fragment of one of the rafters over a length of about 3 m.

4 Method of Building Restoration with the Reuse of its Parts and Assessment of Environmental Efficiency Indicators

The main idea of the warehouse building restoration project was to preserve as many elements and structures as possible that survived the emergency beyond design loads, thereby saving funds, reducing construction time, and minimising environmental impact.

Based on the technical inspection results, elements in a critical state were dismantled: building envelopes, technological equipment, engineering networks, the entire structure of the technological tiered rack, and the roof purlins. Concrete elements were cleaned of organic decomposition products (food products stored in the warehouse), soot, carbon deposits (from the fire), and residues of toxic missile fuel. A geodetic survey conducted before partial dismantling established deviations of the columns from their design position at the eave node level of 20–30 mm.

The dismantling of the damaged tiered rack frames and the expedition roof beams revealed that the rigidly fixed columns had significant residual stresses resulting from their combined action within the deformed structural scheme of the building frame as a whole. Therefore, column positions were repeatedly measured after the complete dismantling of the rafters in the main part of the warehouse (Fig. 5).



Fig. 5. Condition of the building frame after the dismantling of the roof structures.

The point cloud of the steel columns' actual positions was compared with the frame design model. The deviation of the top of the main frame columns after their release from

the rafters showed significant residual deformations, including twisting of the column cross-sections and deviations from the design position of 30–70 mm. The gable posts sustained deviations of up to 400–500 mm with bends along the length of the element up to 150 mm. At the same time, the position of the lower parts of the columns (at a height of up to 1 m from the floor level) practically coincided with the design position, and deviations did not exceed ±5 mm.

Based on the survey results, a building restoration project was developed, which included the following measures:

- cutting the existing main columns of the building at a height of 1 m from the floor level, gable columns at a height of 300 mm, and expedition columns at 500 mm;
- development of connection nodes for the new building frame with the remains of the existing columns;
- all foundations, the plinth wall, and the building's concrete floor were left intact. The project provided for local repair of the floor structure and restoration of the surface with epoxy self-levelling compounds.

The use of existing lower parts of the columns, all foundations, the plinth wall, and the concrete floor in the restored building reduces the cost of reconstruction, the duration of construction work, and the amount of construction waste (approximately 900 tons of concrete) compared to complete demolition and new construction. Even a partial decision to fully replace the frame columns would have necessitated dismantling more than 70% of the entire floor structure and most anchor bolts, requiring their replacement with chemical anchors, which in turn could affect the overall reliability of the restored building.

To quantify the environmental impact, environmental performance indicators were used: primary energy consumption, expressed as total non-renewable primary energy (PENRT, MJ), and global warming potential (GWP, kg CO_2-eq). PENRT and GWP were chosen because they directly quantify the demand for non-renewable energy sources and greenhouse gas emissions, which are the main drivers of climate change in the built environment. These indicators were calculated for all foundations, the plinth wall, and the concrete floor of the building based on data from established databases (Ökobaudat [7]) according to a simplified scheme (phases A1–A3 "cradle-to-gate"), based on the assumption that the building would have been completely dismantled and rebuilt in the same dimensions and structures.

For the total volume of construction materials – concrete classes C8/10, C12/15, C20/25, steel (reinforcement and plate elements), and extruded polystyrene for all foundations, the plinth wall, and the concrete floor of the building – the obtained indicators were PENRT $\approx$ 640,000 MJ and GWP $\approx$ 75,000 kg CO_2-eq.

Thus, even a simplified analysis of environmental indicators demonstrated the expediency of the structural reuse strategy for post-war reconstruction, aligning with the principles of the circular economy.

5 Conclusions

The study, conducted on the example of a warehouse building damaged by an explosion, confirmed the technical feasibility and economic and environmental expediency of the strategy for the partial reuse of existing structural elements in the reconstruction of buildings and structures. This approach requires greater costs for technical inspection, full control by the design organisation over demolition, and the execution of intermediate variable calculations for the installation of a new structural system with maximum use of preserved elements from the previous building.

The connection nodes of the steel columns to the foundations, the monolithic reinforced concrete foundations themselves, the plinth wall, and the concrete floor maintained their load-bearing capacity and suitability for continued operation after sustaining significant, beyond-design emergency loads. Using these elements in the restored building made it possible to significantly reduce the volume and duration of construction work; the amount of construction waste generated (≈900 t of concrete); non-renewable primary energy consumption (PENRT ≈ 640,000 MJ); and lower the global warming potential (GWP ≈ 75,000 kg CO_2-eq) compared to the option of complete demolition and new construction of these structures. The approach demonstrated in this work can serve as an important tool for reducing economic, resource, and environmental losses during large-scale post-war reconstruction in Ukraine or in the restoration of buildings and structures affected by other emergencies.

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Simplified Method for the Strength Verification of Steel Beams with Deviation from Straightness for Their Reuse

Volodymyr Semko[1](✉) and Nataliia Mahas[2]

[1] Poznan University of Technology, Poznan, Poland
volodymyr.semko@put.poznan.pl
[2] Slovak University of Technology in Bratislava, Bratislava, Slovakia

Abstract. The paper presents a simplified rapid assessment method for evaluating the load-bearing capacity of hot-rolled steel beams (I-beams, channels, and Z-sections) with initial horizontal curvature. The main objective of the work is to assess the technical feasibility of reusing such elements in new construction and reconstruction projects. This allows for transforming damaged or deformed steel beams from waste into a valuable resource, significantly extending their life cycle and reducing the need to produce new steel structures. The computational approach is based on accounting for additional torsional stresses arising from geometric imperfections. Experimental studies of beams with a span of 1.5 m and significant deviations (40–60 mm) confirmed that, even with deformations exceeding regulatory tolerances, the elements maintain a sufficient safety margin for continued operation. The proposed methodology provides engineers with a reliable tool for rapid decision-making on the safe reintegration of non-ideal steel profiles into construction production, a key step towards implementing circular economy strategies.

Keywords: Steel Thin-Walled Beams · Torsion · Curved Beams · Damages · Structural Reuse · Life Cycle Extension · Circular Building Components

1 Introduction

Recent trends in building science are increasingly focused on reducing greenhouse gas emissions at all stages of construction – from the manufacturing of building materials and structures to their disposal. One method for reducing CO_2 emissions and economic costs is the reuse of elements. At the same time, until the development of the second generation of Eurocodes [1], the very concept of an "existing" structure was practically unregulated, as it must first exist to be reused. This necessitates a fundamental shift in the design approach, because when designing new structures, engineers rely on idealistic concepts of elements – their shape, physical and mechanical properties, etc. The geometry of structures is assumed to be virtually ideal, with some influence from "accidental" geometric imperfections. Such an approach cannot be applied to existing structures, as

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in most cases, engineers can clearly determine both the materials' physical and mechanical properties and the structure's geometric parameters. After assessing the technical condition of an existing structure, a conclusion can be drawn regarding its compliance with EN 1993 [2] and EN 1090-2 [3]. In case of compliance, reuse is possible. Full compliance of an existing structural element with the requirements of current standards is more often the exception than the rule, as in most cases, the need for dismantling arises for structures in unsatisfactory condition or after significant accidental impacts – fire, earthquake, explosions. Wars also result in a large number of elements, including steel ones, that can be reused, even though they may not meet the requirements of EN 1090-2 [3]. One common defect of steel beams is curvature in the horizontal plane. Analysis of regulatory documents from other countries [4, 5] indicates that the use of curved structures is entirely possible – for example, for buildings with low consequence classes.

One of the main barriers to the large-scale reuse of steel elements is the lack of simple, rapid, and accessible methods for assessing the load-bearing capacity of non-ideal profiles (e.g., curved or damaged) [6, 7]. Modern approaches to circular construction actively implement the concept of material passports [8], which record all physical, mechanical, and geometric characteristics of elements for their safe reintegration after dismantling. The simplified methodology proposed in this work can be an important component of the algorithm for assessing the suitability of steel beams for inclusion in such a passport: it allows rapid on-site determination of the load-bearing capacity of a curved element and confirms its compliance with reuse requirements [9]. Furthermore, the reuse of steel is significantly more efficient than recycling, as it allows for the preservation of almost all embodied energy without the energy costs of remelting. According to current meta-analyses, direct reuse reduces the global warming potential (GWP) by 40% compared to recycling and by up to 97% compared to producing new steel, providing embodied energy savings of 90–95% [10, 11]. Therefore, the aim of this work is to present a simplified methodology for assessing the strength of a steel beam with deviations from straightness in the plane perpendicular to the bending plane for the purpose of its reuse.

2 Simplified Methodology for the Strength Verification of Beams with Curvatures

Modern methods for analysing steel structures using the finite element method enable calculations of structures with various types of imperfections and damage. At the same time, the cost of such calculations can exceed that of a new structure, not to mention the cost of existing elements. To evaluate the strength of existing structures, it is advisable to use rapid assessment methods that enable on-site decision-making on the feasibility of preserving a damaged element and its careful dismantling.

The issue of calculating steel beams with initial curvature in the horizontal plane (Fig. 1) was considered by A.R. Rzhanitsyn [12]. Based on the theory of thin-walled rods by V.Z. Vlasov [13], he proposed a theory for calculating I-beams with horizontal curvature. The goal set by A.R. Rzhanitsyn was to maximise the utilisation of steel beams damaged during the Second World War. Work [12] describes in detail the procedure for

determining the additional forces arising in a steel I-beam that has received an initial horizontal curvature. The beam's curvature was assumed to be a parabola. However, this problem remained undescribed for beams with channel and Z-sections.

The work by Hudz S. et al. [14] is dedicated to the theoretical solution of the problem of finding the allowable curvature of beams.

a)



b)



Fig. 1. Examples of beams with overall out-of-plane curvature from the moment action: a) I-beam roof purlins after a fire; b) channel purlins after a fire.

In this work, the authors have supplemented the methodology proposed by A.R. Rzhanitsyn for I-beams with recommendations for the analysis of steel beams with channel and Z-sections and have also verified it experimentally.

In work [12], the author established the principle that in a beam with horizontal curvature, in addition to normal stresses from bending, torsional stresses also arise, i.e.:

$$\sigma = \sigma_{bend} + \sigma_{\omega}, \tag{1}$$

where σ_{bend} – normal stresses arising from bending, σ_{ω} – normal stresses arising from the warping (torsion) of the cross-section.

In the general case, the warping stresses are determined by the formula:

$$\sigma_{\varpi} = -E \cdot \theta'' \cdot \varpi, \tag{2}$$

where E – modulus of elasticity of steel, θ'' – second derivative of the twist angle function, ω – sectorial area at the point where the stress is determined.

The laws for determining additional torsional stresses, as presented in [12], are shown in Table 1.

Table 1. Additional torsional stresses in the beam.

	Type of load	
	Concentrated force at mid-span	Uniformly distributed load
σ_{ϖ}	$2 \cdot \frac{P \cdot f}{\ell} \cdot \frac{E}{G} \cdot \frac{\omega}{I_t} \cdot v$	$q \cdot f \cdot \frac{E}{G} \cdot \frac{\omega}{I_t} \cdot v$
v	$1 - \frac{th\left(k\ell/2\right)}{k\ell/2}$	$1 - \frac{th\left(k\ell/2\right)}{k\ell/4} \cdot \frac{th\left(k\ell/2\right)}{k\ell/4}$

In Table 1: P – concentrated force; q – uniformly distributed load; f – beam camber (deflection arrow); G – shear modulus; $k = \sqrt{\frac{GI_t}{EI_{\varpi}}}$ – torsional characteristic; It, I_{ω} – torsion constant and sectorial moment of inertia, respectively; ℓ – beam span.

While the coefficient v in Table 1 accounts for the type of loading, the sectorial area ω accounts for changes in stress due on the type of cross-section. This is particularly evident from formula (2). By multiplying the ω diagram by the constants E and θ'' (for a specific load value), we obtain the σω diagram.

For the cross-sections considered in the article (Fig. 2), the sectorial area diagrams are shown in Fig. 3.

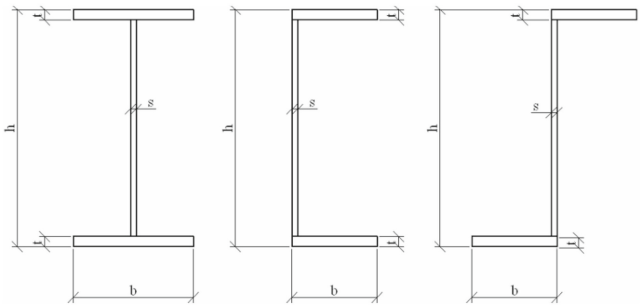


Fig. 2. Beam cross-section diagrams.

In Fig. 3b, the parameter α_x is the distance to the centre of torsion, which is determined by the formula

$$\alpha_x = -\frac{b^2 \cdot t}{2 \cdot b \cdot t + \frac{h \cdot s}{3}} \tag{3}$$

where *b, t, h*, and *s* are the geometric parameters shown in Fig. 2.

In Fig. 3c, the parameter d is the distance from the web face to the zero sectorial coordinate, determined by the formula

$$d = \frac{b^2 \cdot t}{h \cdot s + 2 \cdot b \cdot t}, \tag{4}$$

where *b, t, h*, and *s* are the geometric parameters shown in Fig. 2.

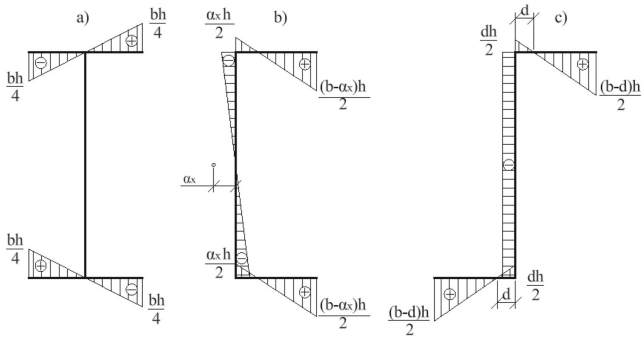


Fig. 3. Sectorial area diagrams for different types of cross-sections.

3 Experimental Verification of the Proposed Methodology

To verify the presented methodology for calculating steel beams with horizontal curvature, tests were conducted on three steel beam specimens. The specimens were made of hot-rolled I-beams No. 10 and No. 12 [15]. The overall bending of the beams ranged from 4 to 6 cm. The beam spans were 1.58 m, 1.59 m, and 1.61 m. The testing of the specimens was carried out on a special setup (Figs. 4 and 5) that allowed the application of a concentrated force without preventing torsional deformations.

The twisting of the cross-section was measured using an optical quadrant. During the experiment, a twist of the beam cross-section with a maximum angle of 8°19′ was recorded.

According to the experimental data, the maximum stress in the cross-section of specimen B1 (I-beam No. 10, deviation from straightness ($d_{fs} = 4$ cm) was 109.2 MPa, 163.8 MPa, and 254.1 MPa (assuming Hooke's law) under loads of 10 kN (moment in the section M = 3.75 kNm), 15 kN (M = 7.5 kNm), and 20 kN (M = 11.25 kNm), respectively, which is 36% higher than the stresses in a non-curved beam.

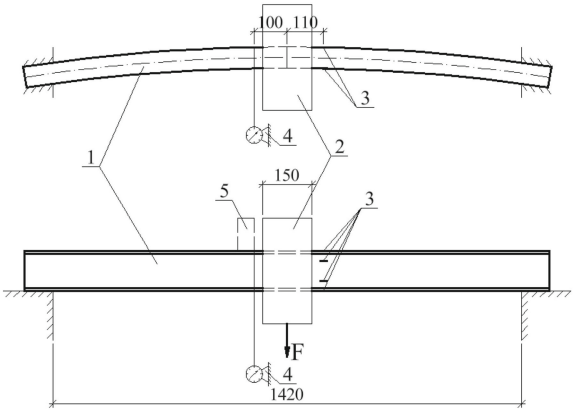


Fig. 4. Diagram of the experimental setup for the bending-with-torsion test: 1 – tested specimen, 2 – steel ring, 3 – strain gauges, 4 – deflection gauges, 5 – optical quadrant.



Fig. 5. Photo of the experimental setup.

When comparing the diagrams for specimens B2 (I-beam No. 12, $d_{fs} = 6$ cm) and B3 (I-beam No. 12, $d_{fs} = 4$ cm), it can be concluded that with a slight increase in horizontal bending (from 4 cm to 6 cm), normal stresses increase significantly (by 26%).

When plotting diagrams based on the experimental data, the development of stresses due to cross-sectional torsion in the I-beam flanges is clearly visible. In pure bending, the theoretical stress diagram in the I-beam flanges would have the shape of a rectangle. Adding the diagram shown in Fig. 3a yields a trapezoidal diagram, as observed during the experimental studies (Fig. 6).

The results of stress calculations using the simplified methodology, compared with those from strain gauges, for specimens B1 and B2 (under a concentrated force F = 10 kN at mid-span) are presented in Fig. 6. The results correlate well, and the remaining discrepancies are due to the accuracy of the measuring instruments and the impossibility of creating ideal conditions for such an experiment.

All of the above leads to the conclusion that the calculation methodology presented in Sect. 2 for analysing steel beams with initial horizontal bending is sufficiently accurate and can be recommended to engineers for further application in the practice of new construction and in the verification calculations of steel beams in operation.

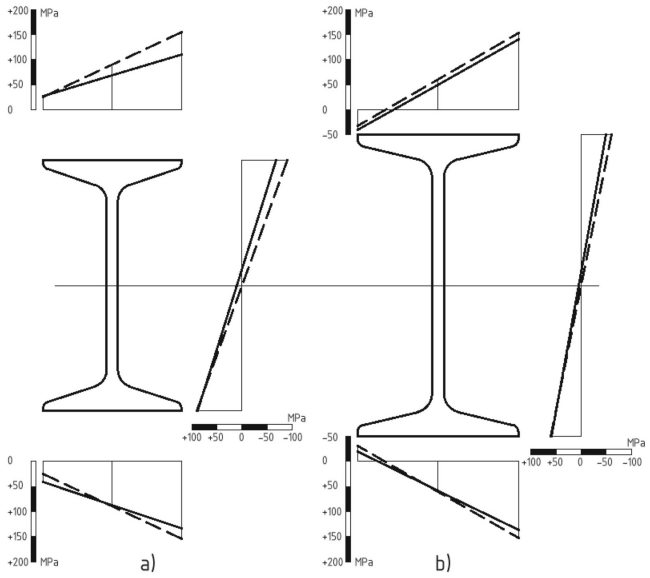


Fig. 6. Diagram of normal stresses in the cross-section of a curved beam under a load of 10 kN: a) specimen B1, b) specimen B2.

4 Conclusions

The methodology presented in this work allows the determination of stresses in beams that have developed a smooth curvature (described by a parabolic function). The methodology can be used both for beams damaged under load and for the calculation of new curvilinear beams. The calculation can be performed for three types of beam cross-sections – I-beam, channel, and Z-section – as well as for the two most common types of loading: a concentrated force at mid-span and a uniformly distributed load. The assumptions underlying the emergence of torsional normal stresses in the methodology were confirmed by experimental studies. The implementation and use of this methodology in the practice of sustainable construction allows for reduced costs in expert assessments of the technical condition of steel beams with this type of damage. It also shortens the decision-making time regarding the possibility of reusing beams with horizontal bends.

By implementing the proposed rapid assessment method, it is possible to significantly increase the share of direct reuse of steel beams. According to surveys of demolition companies in the UK and Europe, currently only about 5% of steel elements are directly reused, while the rest are sent for remelting [16]. The use of simple assessment tools like the one proposed will allow for the saving of thousands of tons of steel from remelting annually in just one region, transforming potential waste into a valuable resource for

new construction and renovation. The embodied energy savings from reusing one steel beam compared to producing a new one reach 90–97%, and compared to recycling, 40–80%. This directly reduces the whole-life carbon of buildings and contributes to achieving circular economy goals, overcoming barriers related to material passports, and transitioning from a linear to a regenerative construction model [10, 11]. Salvaged and reused steel beams reduce both economic costs and the construction process's carbon footprint.

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Disposal, Recycling or Reuse? End of Life and Circularity of Modular Panels in Canada

Robin Hilbrecht[1], Manuela Almeida[2], Ricardo Mateus[2], Christopher Baldwin[1], and Cynthia A. Cruickshank[1](✉)

[1] Faculty of Engineering and Design, Centre for Advanced Building Envelope Research, Carleton University, K1S 5B6 Ottawa, Canada
robinhilbrecht@cmail.carleton.ca, CynthiaCruickshank@cunet.carleton.ca

[2] Department of Civil Engineering, Institute for Sustainability and Innovation in Structural Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal

Abstract. For modular building envelope construction in Canada, panelization is implemented through multiple manufacturing methods. While panelized systems can reduce construction time and cost, less well known is their end-of-life (EoL) impacts and reuse potential after building demolition. Current Canadian construction and demolition of panels tend towards landfilling rather than reuse. Modular panel manufacturing methods include fused panels where insulation is permanently attached to a sheathing board, such as sandwich insulation panels, or prefabricated panels which allow for full component disassembly at EoL. This paper compares EoL performance between these two methods, where both panels use cement fibre boards as the sheathing component. Using publicly available environmental product declaration data, life cycle assessment (LCA) EoL impacts are calculated for the demolition scenarios for the same functional unit. Exploring future circularity potential through a literature review of strengths, weaknesses, opportunities, and threats (SWOT) analysis clarifies the end of life and reuse potential of both panel types. A discussion of Canadian policies, markets, construction practices, and material quality assessments required for reuse identifies barriers and future opportunities.

Keywords: modular construction · sheathing panel · reuse · building envelope · end-of-life

1 Introduction

Considerations of end-of-life (EoL) impacts and circularity for modular building elements are in early development in Canada, with modular building still a relatively novel practice in industry [1]. How a modular panel manufacturing practice impacts the EoL circularity is essential for understanding the long-term impact of new building techniques. This study analyzes the EoL impacts of two different panel designs that serve the same function of a building sheathing panel, one with an encapsulated (fused) design and the other with a built-up panel designed for disassembly (DfD).

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Circularity with respect to buildings aims to reduce new material production and use by integrating existing building materials into new constructions through recovery, retention, and reuse [2]. Consideration of how materials are reused at the end of life, and reducing demolition waste are integrated into strategies for future building codes and environmental policies [3].

Parallel to the research and development of circular economy practices in building construction is the development of modular integrated construction, or prefabricated construction methods [4]. Prefabricated components, such as structurally insulated panels with an exterior sheathing board and insulation, are becoming more common in Canadian buildings as a method of modular construction [4].

While modular construction principles may allow for reduced construction waste, given the greater potential for automation and factory/off-site manufacturing [5], there has been little focus on EoL impacts of modular components. A concern is that some of the focus on assembly speed and energy performance of prefabricated components may limit circularity [4]. Quantitative analysis of the EoL impacts of modular buildings is limited. Wen et al. [6] conducted a case study of high rise steel framed buildings in Hong Kong comparing the EoL impacts of a modular constructed system with a built-on-site case. Findings indicated carbon emission reductions for the modular case, with even more reductions if materials could be reused. The EoL transportation emissions materials were still significant in both cases [6]. More research concerning EoL and circularity of materials would fill a gap in understanding the impacts of this modular construction trend.

This research examines sheathing panels, a sub-component of a modular system, that can be used in new construction or building retrofit projects. The panels have integrated insulation, structural support, air and vapour barriers, and fire resistance that would be seen in multi-unit residential, commercial, or industrial buildings. Sheathing panels are used in Canadian buildings since both thermal performance and construction efficiency are desirable in the Canadian construction industry [7]. There are guidelines and standards for mechanical and thermal performance of structural insulated panel (SIP) systems in Canada, but there is a lack of regulation for LCA and EoL performance reporting for these applications [7]. Sheathing panels can either be constructed of exterior sheathing with a fused insulation [7], or as a built up panel with bio-based insulation [8, 9].

This paper focuses on EoL impacts of building envelope panels using exterior fibre cement sheathing boards, including boards containing Magnesium Oxide (MgO) for construction in North America [10]. The sheathing boards were components of a cradle-to-gate LCA in British Columbia by Li et al. [11], which compared MgO SIP systems to framed-in-place sheathing panels. Given the high environmental impact of initial raw material production [6], especially in cement, reuse of modular panel systems or components can reduce the long term environmental impact of buildings.

In Canada, construction material reuse focuses mainly on individual building components such as structural steel, framing materials, and masonry [12]. Material reuse in buildings in Canada varies regionally and tends toward project specific initiatives [1]. For some municipalities, there are guidelines for reducing construction waste and for careful deconstruction, such as Vancouver's diversion threshold of 75% for clean wood [1]. Incentives for material circularity in Canada do exist, such as the Canadian

Standards Association (CSA) guideline CSA-Z782–06 for design for disassembly and adaptability in buildings [13]. Prefabrication companies are also involved in adaptive reuse and circularity, but not yet at a level of market maturity [1].

Given the early development in building circularity economy practices in Canada, and varying modular construction methods, this paper aims to determine EoL impacts of two modular sheathing panel designs, with either existing demolition ("business-as-usual") or circular reuse paths.

2 Materials and Methods

Quantitative and qualitative methods were used to consider the EoL impacts of both modular panel systems. The business-as-usual EoL scenario for the panels is examined using quantitative methods. A future scenario, using circular economy principles, is explored using a qualitative literature synthesis in the form of a SWOT analysis.

The modular panel construction methods are referred to as (1) a 'fused panel' and, (2) a 'design for disassembly (DfD) panel'. The fused panel is a sheathing board where insulation is permanently attached to a panel coated with air and vapour barriers. The DfD modular panel design is built of individual elements. That is, it is designed for disassembly into individual components at the end of life, including exterior vapour barrier, sheathing, lightweight steel framing, and insulation.

The design for the DfD panel was adapted from the cellulose retrofit panels previously tested and reported on by Natural Resources Canada [8, 9]. Panel components and the weight of functional units are given in Table 1.

Table 1. Panel composition with EPD reference by material

System	Fused panel	DfD panel
Materials	MgO sheathing board, polyurethane rigid insulation foam (PUR) [14]	Gypsum core fiberglass sheathing board [15], loose fill cellulose [16], membrane [17], steel framing [18]
Panel mass per functional unit	9.2 kg	9.92 kg

For the quantitative analysis, EoL stage LCA impacts (C1-C4) are calculated based on environmental product declaration (EPD) values. The masses of construction waste and recyclable material for each panel design are also determined. Panel designs are based on a functional unit of 1 m^2, with a thermal resistance (R value) of 1 m^2K/W. EPDs collected used TRACI 2.1 methods for North American markets, in accordance with ISO 14025 and ISO 14044. Where possible, product specific EPDs were used, for the fused panel [14], sheathing board [15], cellulose [16], and membrane [17], but a sectorial average EPD was used for the framing [18].

There can be high uncertainty in the EoL LCA data [6], so this paper provides comparisons between systems, rather than an absolute authority on environmental impacts of each system.

The qualitative impacts in a circular economy EoL scenario are considered through a literature review grounded in the strength, weakness, opportunities and threats (SWOT) analysis method. Many SWOT analyses of building construction use a combination of a literature review and surveys, such as Sesana et al. [19]. This project uses a literature review for SWOT analysis, with potential future work to develop research questions and surveys for the architecture, engineering, and construction (AEC) industry.

3 Results and Analysis

3.1 Business-As-Usual EoL Scenario

For EoL environmental impact, LCA impacts for scopes C1 to C4 were calculated for both panel designs as seen in Table 2.

Table 2. EoL impacts for LCA scope C1, C2, C3, C4 inclusive

Impact Category	Fused	DfD
Global warming potential (GWP) [kg CO_2 eq.]	2.12E-01	1.29E+00
Ozone depletion potential (ODP) [kg CFC-11 eq.]	5.49E-05	6.67E-09
Acidification potential (AP) [kg SO_2 eq.]	4.46E-09	2.20E-03
Eutrophication potential (EP) [kg N eq.]	7.08E-04	2.25E-03
Smog formation potential (SFP) [kg O_3 eq.]	1.60E-02	4.33E-02
Abiotic Depletion Potential -fossil fuels (ADPF) [MJ]	1.4E+00	1.08E+00

Depending on the impact category, each panel design can perform better than the other, as visualized in Fig. 1, with impact value max normalized using Eq. (1), where NV is the normalized value, V is the value given for the panel in Table 2, and V_{max} is the maximum value for impact category between the two panel designs.

$$NV = V/V_{\max} \tag{1}$$

In terms of GWP, the fused panel has a lower environmental impact, likely due to the lack of steel framing. The fused panel has higher ADPF impacts, and the DfD panel has a higher GWP impact.

Transport of demolished materials can be a significant factor in EoL impacts [6], so the mass of waste was calculated for each scenario, as seen in Table 3, using stated waste and recycling rates from EPD documents.

For the fused panel, screws that would be included in the functional unit were partially recycled but the rest of the construction waste is going to the landfill. For the DfD panel, 92% recycled steel was assumed based on the product EPD. Even though the design for disassembly panel could theoretically have higher recycling or reuse rates by disassembly of individual components, this base EoL scenario assumed that contractors would still follow typical landfilling practices for the fibre cement board, cellulose insulation, and membrane. The overall masses of waste to landfill for each panel are within 1.2% of each other (9.22 kg vs. 9.33 kg).

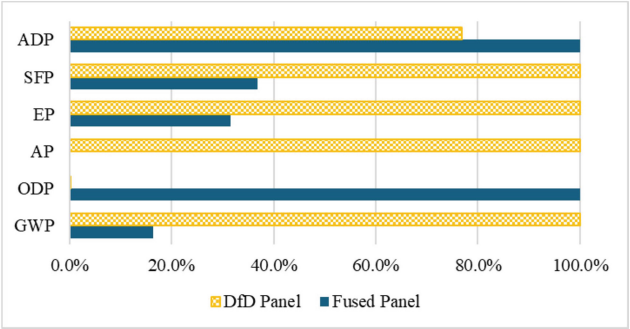


Fig. 1. Normalized LCA EoL impacts by panel

Table 3. Panel Waste Quantities

	Fused panel [14]	DfD panel
Mass as mixed construction waste [kg]	9.27	9.92
Waste to landfill [kg]	9.22	9.33
Waste to recycling [kg]	0.053	0.460
% Total mass recycled	0.58%	4.64%

3.2 Circular Economy End-of-Life Scenario

This synthesis of threats and weaknesses drew upon barriers discussed by Wuni and Shen [20] in their review of barriers to adaptation of modularity in construction. Both panel designs would experience shared barriers to reuse in circular applications such as costing accuracy [1], risk aversion by contractors and customers, or excessive regulation on used materials [21]. Still, there are differences in how each panel could be used in circular applications, as described in Tables 4 and 5.

Table 4. SWOT of circularity of fused panel

Strengths	Labour savings in demolition – full panels, ease of reuse for complete panel
Weaknesses	Damage risk in disassembly which may result in the full panel becoming unusable (process barrier), minimal recyclable materials (technical barrier)
Opportunities	Material traceability for a panel market as fused panels can be more easily stored and transported as complete products, minimizing perceived risk [21]
Threats	Lack of market for fused panels (financial barrier), lack of material testing standards for full panel (knowledge and process barriers) [1]

The fused panel best case scenario for circularity is full reuse of all panels; a more likely scenario is to reuse and storage of the largest undamaged panels with debonding of

cement fibre boards and insulation to downcycle materials where possible [1]. Worst case for the fused panel is even with reuse as a goal, materials are damaged and can only be landfilled. As a building element, the fused panel can be easily traced, as all components are together in the panel. DfD panel is designed for adaptation and flexibility; individual components will require more care to ensure traceability but are easier to reuse in multiple applications.

Table 5. SWOT of circularity of DfD panel

Strengths	Components can be reconfigured for different applications if select parts of the panel are damaged [6], lighter weight of materials, reducing individual transport impacts
Weaknesses	Increased labour time in disassembly [21], potential breakage and damage of fibre cement sheathing during deconstruction (technical barrier)
Opportunities	Simpler market for individual components compared to whole panel (aesthetic barrier and use flexibility)
Threats	More documentation for a material bank required for each component (process barrier)

In terms of circularity, many researchers assume when conducting quantitative EoL analysis that a market for materials will exist (e.g., see Wen et al. [6]). This is a threat for the fused panel, as the complete panel component is less likely to be in demand across a broad range of building applications compared to individual elements in the DfD panel.

The central difference between the two panel designs is the level of disassembly possible – the strength of the fused panel is in its traceability as a single component. The fused panel may be faster to deconstruct as a single piece without damage to the cement fibre board compared to the DfD panel. If the DfD panel requires full disassembly there are weaknesses in the time to deconstruct, and a threat with traceability.

Expanding on this analysis, future research could survey stakeholders in the AEC industry regarding priorities for material reuse related to modular panels. A survey could explore whether traceability and storage (fused panel) or full material reuse and ease of recycling (DfD) is more desirable. As new panel designs and manufacturing methods are introduced, it is essential that new materials are not having high impacts to the environment, or create an environmental burden at end of life [3].

4 Conclusion

EoL scenarios for two novel modular panel designs in Canada using current landfilling scenario and circular economy potentials in future practice were presented.

The current practice EoL scenario based on publicly available EPD data showed the environmental impacts in the C1 through C4 scope were close in scale, with no design having the least impact in all LCA categories. This quantitative analysis is limited by EPD availability for materials that includes C1-C4 impacts.

While the current EoL accounting did not conclusively determine if one panel design was preferred, the circular economy analysis for EoL raised important questions on how diverging priorities of stakeholders will influence which panel is desired. While fused panels may not have a guaranteed market, they are more traceable and faster to deconstruct. A DfD style panel may be slower to deconstruct, with more potential for damage to the cement sheathing board, but it will likely have a better reuse market for individual components and potentially reduce transportation impacts through reduced weight of individual components.

This is an early exploration of the EoL scenarios for modular panels. Further research on circularity in initial designs using prefabricated panels is recommended, especially direct consultation of the AEC industry and on-site experience.

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Enhancing Natural Fibre Textile Reinforcement – Effects of Impregnation Materials and Methods

Malte Kaliske(✉) and Marcus Ricker

Chair of Structural Concrete, TU Dortmund University, Dortmund, Germany
malte.kaliske@tu-dortmund.de

Abstract. In recent years, the importance of non-metallic reinforcement made of natural fibres has been gaining relevance. Previous investigations have suggested that impregnation is a critical aspect for the mechanical and long-term performance of concrete components reinforced with natural fibres.

This study aims to understand the influence of distinct impregnation methods and materials, namely mechanical rolling and vacuum impregnation, on the mechanical performance, bonding behaviour, and durability of natural fibre yarns intended for textile-reinforced concrete.

To this, reinforcements made of sisal, hemp, and flax yarns, as well as selected hybrid configurations, were systematically examined. The tensile properties were determined prior to textile production in accordance with a standardised fibre strand testing procedure. Multiple specimens were tested to capture the material variability and to evaluate the resulting variation in stiffness and strength.

The results indicate that strength, stiffness, and scatter varied substantially depending on material and processing method. Vacuum impregnation increased the modulus of elasticity from 1.8 up to 2.2 times compared to the rolling impregnation with notable differences across yarn types and combinations. Additionally, the results suggest that appropriate pairing of yarn material and impregnation technique can significantly enhance load-bearing capacity and control deformability.

This study provides a systematic comparison of impregnation techniques for various natural fibre yarns, showing how these methods interact and influence mechanical performance. The comparison supports the selection and combination of suitable yarns and impregnation techniques for textile reinforcements in structural concrete. It also identifies opportunities for further optimizing natural fibre reinforcement systems to achieve durable and structurally efficient concrete components.

Keywords: Natural fibre textile reinforcement · Textile-reinforced concrete · Impregnation methods

1 Introduction

In recent years, the importance of non-metallic reinforcement in concrete construction has steadily increased, with synthetic fibres such as carbon, glass, and basalt being predominantly used (e.g. [1–3].). Although these materials exhibit excellent mechanical

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properties and high resistance to corrosion, their production is often energy-intensive, costly, and associated with a considerable CO_2 footprint [1, 2, 4, 5]. Against this backdrop, natural fibres have increasingly come into focus as a sustainable and cost-effective alternative [1, 6, 7]. Plant-based fibres such as hemp, flax, and sisal are widely available in multiple geographic regions, are environmentally-friendly, thereby, offering the potential to replace conventional synthetic fibres in various composite materials [6, 7].

Despite these benefits, the widespread application of natural-fibre textiles in reinforcement technology still faces significant challenges due to their mechanical performance and durability [1, 6, 7]. A central issue is the degradation of the fibres in the highly alkaline environment of concrete, which can reduce their long-term bond and load-carrying capacity [6, 7]. Furthermore, natural variations in fibre thickness, purity, and inherent mechanical properties increase the complexity of their industrial production process, leading to increased variability in material characteristics [6–8]. To overcome these shortcomings, the impregnation of textiles is essential to improve the internal cohesion of the fibres and to protect them from external chemical influences. Impregnation is also relevant for the handling and placement of the textiles into [6–8]. Natural fibres exhibit inherent material variability, including variations in thickness, purity, and mechanical properties due to their botanical origin and cultivation conditions. This variability complicates industrial textile processing and increases scatter in material properties, ultimately affecting mechanical performance and structural reliability [6, 8]. To ensure their long-term durability, an impregnation process is indispensable. Impregnation not only enhances the internal bond between the individual filaments but also provides a protective barrier against the chemically aggressive and highly alkaline environment of concrete. Without this protection, the fibres would deteriorate rapidly, limiting their structural applicability.

This study examines the mechanical behaviour of sisal, hemp, and flax yarns for use in textile reinforced concrete. It focuses on the influence of impregnation materials and methods, comparing mechanical rolling and vacuum techniques, using standardized yarn tow tests, as those described in [9], to determine tensile strength and elastic modulus. The results support the targeted design of natural fibre reinforcements with controlled deformability for structural concrete applications.

2 Materials and Methods

2.1 Natural Fibre Yarns

The selection of natural fibre yarns for textile reinforcement focused on sustainable alternatives such as hemp, flax, and sisal. To function effectively in concrete reinforcement, these yarns must exhibit high tensile strength and a high modulus of elasticity.

The mechanical properties of the investigated unimpregnated yarns are summarised in Table 1.

For this study, the yarns with the largest cross-sectional areas—specifically Hemp 3333 tex, Sisal 4545 tex, and Flax 3000 tex—were selected for further processing. This selection ensures that the reinforcement can carry sufficient tensile forces after cracking. A larger yarn diameter improves tensile load uptake and thus enhances force transfer to the concrete matrix.

Table 1 Mechanical properties of unimpregnated yarns

Fibre Type	Fineness [tex]	Number of Test specimens	Cross-sectional area [mm^2]	Mean Tensile Strength [MPa]	CV [%]	Mean Modulus of Elasticity [GPa]
Hemp	3333	9	1.5	156.61	7.5	5.95
Hemp	2222	10	2.3	102.14	5.2	4.17
Sisal	4545	10	1.9	173.74	12.9	7.47
Sisal	2222	10	3.9	206.71	17.6	8.98
Jute	2222	10	1.5	149.73	8.1	9.60
Flax	3000	12	2.1	158.18	19.0	7.81

2.2 Impregnation Materials

Impregnation of natural fibre textiles is essential for use in cementitious matrices, providing filament bonding and alkaline protection. This study compares several impregnation systems to balance mechanical performance, bond behaviour, and sustainability, using the bio-based epoxy GreenPoxy 56 as a reference against TECOSIT polymer dispersions (CHT Germany).

The GreenPoxy 56 reference system is characterised by a high bio-based carbon content of up to 56% and delivers good mechanical properties in terms of tensile and flexural strength [10]. Due to its high diffusion density, it acts as an effective barrier against chemical degradation of natural fibres [11]. In practical application, the system manifests itself as reactive. This results in significant exothermicity, especially with larger batches. In addition, it should be noted that these thermosetting systems exhibit characteristic brittle fracture behaviour without additional modification [11].

Specialised polyacrylate-based dispersions, such as TECOSIT CC 1000, were also examined. These systems provide an effective moisture barrier and improve mechanical adhesion [8], although their matrix stiffness is lower than that of high-strength epoxies because they prioritise interface optimisation over forming a highly rigid structure. The TECOSIT CC 7030 and CC 7021 variants allow universal application and precise control of film formation through adjustable glass-transition temperatures. As aqueous systems, they offer a closed barrier against external influences while maintaining practical handling [12].

2.3 Impregnation Processes

In this study, four impregnation variants (VR1–VR4) were systematically examined to assess their effects on wetting quality, structural integrity and the mechanical properties of fibre yarns. The initial variant (VR1) employs a custom-built impregnation device in which the yarn passes over multiple deflection rollers. Upstream and downstream rollers ensure uniform low-tension guidance, while rubber-coated rollers reduce local

tension peaks and promote homogeneous impregnation. This setup enables consistent impregnation while minimising mechanical stress on natural fibres.

Variants VR2 and VR3 are based on the mechanical incorporation of the impregnation media using profiled steel or acrylic rollers. The application of transverse pressure by the rollers facilitates deeper penetration of the impregnation compound into the yarn cross-section, thereby, reducing voids and improving wetting of individual filaments [13, 14]. However, previous investigations have shown that the applied pressure can induce localised fibre damage, resulting in a significant reduction in the modulus of elasticity [15, 17]. This decrease in stiffness is consistent with studies on the treatment of natural fibre bundles, which indicate that lateral compressive loads can cause microscopic fibre breaks or delamination [16, 17].

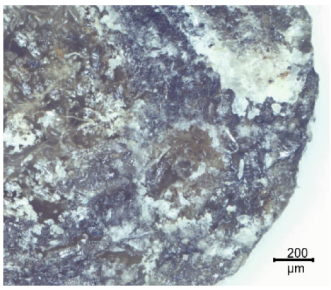
VR4 applies vacuum impregnation, in which the yarns are fully wetted in a vacuum chamber at 20–30 mbar and 20 °C. This method allows the impregnation medium to penetrate deeply into the fibre bundle without mechanical pressure. Microscopic images of VR4 Fig. 1 show a homogeneous matrix–fibre structure, low porosity and a distinct boundary zone without protruding filaments. No structural fibre damage is evident, corresponding to comparatively high elastic modulus values and more consistent mechanical performance. The benefits of low-pressure or pressure-free impregnation are likewise reported in studies on mineral or polymer impregnation of fibre bundles (e.g. [14, 18].).

A direct comparison of the four variants (Fig. 1) shows that VR1 and VR4 are the least invasive and most effective in maintaining yarn integrity. VR1 benefits from controlled, low-stress mechanical guidance, whereas VR4 ensures uniform wetting without fibre damage. By contrast, VR2 and VR3 achieve extensive cross-sectional wetting but compromise structural integrity and stiffness. The findings underline that impregnation of natural fibres requires a careful balance between complete saturation and mechanical protection. This balance is particularly important for textile-reinforced concrete, where both the load-bearing capacity of the textile reinforcement and its durability under alkaline exposure are essential.

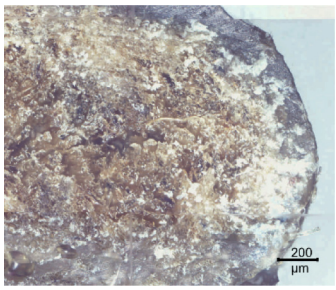
VR1 exhibits uneven impregnation with significant cavities due to insufficient fibre wetting. Mechanical impregnation in VR2 and VR3 improves wetting and reduces cavities, while vacuum impregnation in VR4 yields the highest-quality cross-sections with complete wetting and a homogeneous fibre–matrix structure.

For the GreenPoxy epoxy system, investigations focused on VR1, which met the mechanical requirements and rendered further process variations unnecessary (see Fig. 2). Microscopic analysis of the resulting cross-sections shows nearly complete resin penetration, consistent filament wetting and an absence of interstitial voids. The composite exhibits a clear boundary zone, indicating full filament integration into the consolidated matrix.

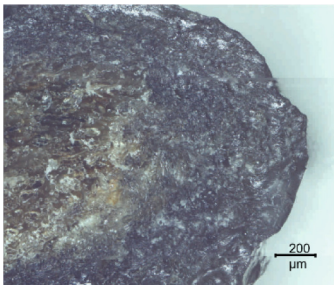
Sisal represents a special case: impregnation with Tecosit CC1000, Tecosit 7030, or Tecosit 7021 was unsuccessful because the low viscosity of these resins caused the yarn to untwist, which made the fibres lose their cohesion and thus partially destroyed the fibre composite structure.



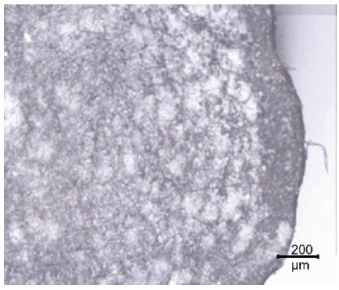
VR1: Impregnation apparatus



VR2: Profiled steel rollers

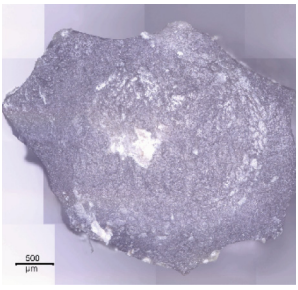


VR3: Acrylic rollers

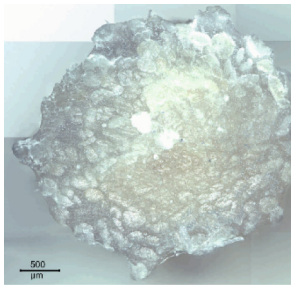


VR4: Vacuum impregnation

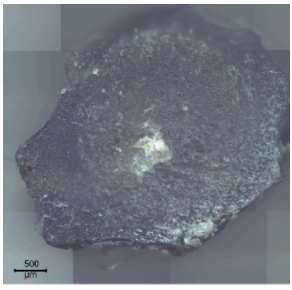
Fig. 1 Cross-section of flax yarn impregnated with TECOSIT CC7021



a) Flax



b) Sisal



c) Hemp

Fig. 2 Cross-section of yarn impregnated with Greenpoxy

3 Results and Discussion

Figure 3 compares the mechanical properties of untreated and impregnated natural fibre yarns, demonstrating the performance enhancement achieved through impregnation. Untreated yarns exhibit low tensile strength and stiffness due to the absence of internal fibre bonding: Hemp (3333 tex) achieved a tensile strength of 156.6 MPa and an elasticity modulus of 5.95 GPa, while flax (3000 tex) achieved 158.2 MPa and 7.81 GPa. Impregnation using the standard VR1 process significantly increased these values. Hemp–GreenPoxy attained 471.5 MPa and 33.57 GPa, and flax–Greenpoxy 392.4 MPa and 29.8 GPa.

These results confirm that impregnation activates the load-bearing potential of natural fibre yarns, preventing premature twisting failure and promoting failure of the fibres within the yarn.

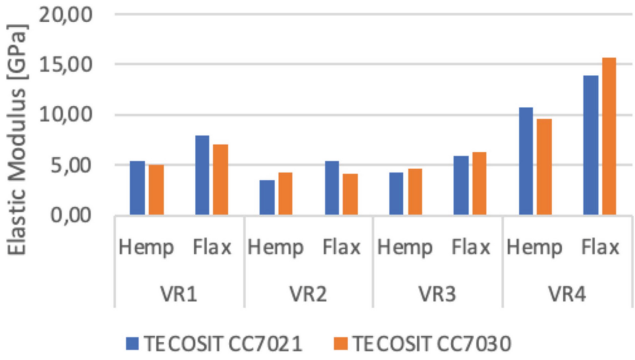


Fig. 3 Influence of the impregnation method (VR1-VR4) on the modulus of elasticity of flax and hemp yarn.

Across all variants, flax exhibited a slightly higher modulus of elasticity than hemp due to its greater intrinsic fibre stiffness. VR1 produced intermediate modulus values, with flax reaching 7.89 GPa (CC7021) and 7.06 GPa (CC7030), both exceeding the corresponding hemp results. VR2 yielded the lowest stiffness overall: hemp achieved 3.48 GPa (CC7021) and 4.26 GPa (CC7030), while flax reached 5.42 GPa (CC7021) and 4.15 GPa (CC7030), indicating insufficient wetting or increased defect sensitivity during impregnation.

With VR3, stiffness increased, giving comparable results for both rolling-based methods. Hemp ranged from 4.22 to 4.60 GPa, and flax from 5.97 to 6.33 GPa. The highest stiffness values occurred in VR4: hemp reached 10.68–9.56 GPa and flax 13.96–15.66 GPa, representing the highest values in the dataset.

The impregnation method strongly influences mechanical performance. In VR2 and VR3, transverse roller pressure damages filaments and reduces stiffness, whereas vacuum impregnation (VR4) at 20–30 mbar achieves complete, gentle wetting of the yarn cross-section. For flax–acrylate 7021, stiffness increased from 5.42–5.97 GPa (rolling) to 13.96 GPa (VR4), an improvement by a factor of 1.8–2.2. This demonstrates that both matrix selection and process mechanics determine the effective utilisation of the fibres.

Load-deformation behaviour is governed by yarn type, matrix properties, and processing conditions. While epoxy systems provide the highest strength, polymer dispersions improve wetting and reduce porosity, offering a balanced performance. For flax yarns impregnated with TECOSIT CC1000 in VR4, a tensile strength of 244.1 MPa and a modulus of 22.41 GPa indicate a favourable stiffness to deformation ratio. Overall, impregnation type, particularly vacuum impregnation, strongly influences mechanical performance, enabling natural fibre reinforcements in textile reinforced concrete to achieve high load capacity and controlled deformability when material and process parameters are optimized.

4 Conclusion

This study demonstrates that impregnation is crucial for enhancing the mechanical performance of natural fibre yarns used as concrete reinforcement. Among the investigated techniques, vacuum impregnation proved most effective, increasing the modulus of elasticity by a factor of 1.8–2.2 compared to mechanical rolling while ensuring uniform fibre wetting and minimal structural damage. Flax yarns showed the greatest improvements in stiffness and strength, whereas sisal required careful processing due to structural sensitivity. Overall, vacuum impregnation combined with bio-based resins such as GreenPoxy offers a promising route toward durable, high-performance, and sustainable textile reinforcements for structural concrete applications.

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Assessment of the Ecological Footprint of Construction and Demolition Waste in Residential Buildings

Carolina Piña Ramírez[1(✉)], Alejandra Vidales Barriguete[2], Patricia Aguilera Benito[2], Julita Krassowska[3], and Verónica Vitiello[4]

[1] Departamento de Construcciones Arquitectónicas y su Control, Universidad Politécnica de Madrid, Escuela Técnica Superior de Edificación, Madrid, Spain
carolina.pina@upm.es

[2] Departamento de Tecnología de la Edificación, Universidad Politécnica de Madrid, Escuela Técnica Superior de Edificación, Madrid, Spain

[3] Department of Building Structures, Bialystok University of Technology, 15-351 Bialystok, Poland

[4] Department of Civil, Building and Environmental Engineering, University of Naples Federico II, Piazzale Vincenzo Tecchio 80, 80125 Naples, Italy

Abstract. This research analyzes the feasibility of obtaining a real Construction and Demolition Waste (CDW) footprint by quantifying and analyzing waste generated in two residential developments. The aim is for the CDW footprint obtained during construction to serve as a reference for similar future projects, enabling more accurate waste management estimates. The methodology combines theoretical estimation and quantitative measurement of construction waste, comparing planned estimates with actual on-site data.

Calculating the CDW footprint revealed significant discrepancies between EGR and PGR estimates and actual waste: up to 18% and 27% less, respectively, for non-hazardous waste, and 400–900 times more than actual for hazardous waste. For Level I CDW, primarily generated during excavation, the footprint ranged from 3.83 m^3/m^2 B/R for one basement to 4.60 m^3/m^2 B/R for two basements. For Level II CDW, the footprint depended on the construction system: 0.50 m^3/m^2 S/R for traditional construction and 0.30 m^3/m^2 S/R for prefabricated or industrialized elements. Hazardous CDW was quantified in mass due to a lack of volumetric data, showing lower values in industrialized constructions (0.000046 t/m^2 S/R) than in traditional ones (0.000075 t/m^2 S/R).

These findings support compliance with current regulations and provide data-driven benchmarks that promote waste minimization and eco-efficient construction practices.

Keywords: Ecological footprint · building · recycling · sustainable construction · construction and demolition waste

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1 Introduction

The implementation of new regulations and revisions of existing frameworks have advanced European targets for waste management, industrial sustainability, and the transition to a circular economy [1–9]. Reliable, real-world data remain essential to assess the effectiveness of these measures and to monitor progress [10–16].

Construction and demolition waste (CDW) requires proper traceability to prevent malpractice and verify circular economy practices, including reuse, recycling, and recovery, as mandated by legislation [17]. CDW represents the largest waste stream in the European Union, comprising approximately one-third of total waste generation [1].

The CDW footprint provides detailed information on waste generation and management, enabling strategies to reduce waste in the design phase, improve recycling and recovery during construction, and promote reuse, especially in demolition. It also contributes to reducing the ecological footprint, a measure of human impact on the environment [18].

Spain has recently updated its regulatory framework with Ley 7/2022, replacing Ley 22/2011 and repealing Orden MAM/304/2002. This law transposes European Directives (EU) 2018/851 and (EU) 2019/904 [2–6]. The law prioritizes waste prevention, reduces landfill disposal, ensures proper management of hazardous and non-hazardous waste, and assigns responsibilities to regional authorities for authorization, inspection, and data management. Digital tools are essential to ensure traceability and interoperability across administrative levels.

Despite regulatory advances and the proliferation of initiatives, significant uncertainties remain regarding the estimation of actual CDW generation, as well as the influence of building typology and the degree of industrialization on these rates. Recent studies highlight the need to validate and refine existing calculation methods through systematic comparisons with experimental on-site data.

In this context, the present study examines the accuracy of current CDW estimation methods used in Waste Management Studies (EGR) and Waste Management Plans (PGR), by comparing theoretical estimates with in situ experimental measurements and analysing the role of construction typology and industrialization level in waste generation.

2 Methodology

Conventional CDW estimation methods are generally based on standardized datasets, often producing generic values that may not reflect real on-site waste generation. Historically, regional construction practices played a major role in shaping waste outputs; in contemporary contexts, building typology and degree of industrialization have emerged as primary determining factors.

To address these limitations, a two-stage methodological framework was implemented, combining theoretical estimation with experimental validation. In the first stage, CDW generation was estimated using the indicators and coefficients defined in the corresponding Waste Management Studies (EGR) and Waste Management Plans (PGR). These documents provided project-level forecasts disaggregated by waste category and referenced surface area or built volume.

In the second stage, experimental data were collected directly on site. Waste was segregated by fraction, classified according to the applicable European waste codes, and weighed using calibrated equipment. The total CDW mass was subsequently normalized by constructed floor area to obtain standardized generation rates (e.g., $t \cdot m^{-2}$), enabling comparison with theoretical values.

The empirical study was conducted on two residential construction projects with comparable characteristics in terms of size, location, and regulatory context but differing in construction system and industrialization level. This design allows isolating the effect of construction typology and industrialization on CDW generation while ensuring that external boundary conditions remain as similar as possible. A comparative analysis was then carried out to assess deviations between theoretical and measured values and to identify systematic biases in current estimation practices.

2.1 Theoretical Estimation

The EEH-AURREZTEN tool developed by Ihobe was used and specifically adapted to comply with the regional regulatory requirements set out in Orden 2726/2009. This tool enables the standardized estimation and characterization of construction and demolition waste (CDW) at project level. In this study, it was applied to both the Waste Management Studies (EGR) and the Waste Management Plans (PGR) associated with the selected residential projects.

Using adapted EEH-AURREZTEN tool, the estimates reported in the EGR and PGR were systematically assessed for several key parameters: total waste generation (in terms of both mass and volume), material densities, waste classification by fraction and hazard level, proposed management and treatment routes (reuse, recycling, recovery, or disposal), and the associated management costs. In addition, the influence of these estimates on the overall construction budget (Construction Cost Estimate, PEM) was examined, in order to quantify the economic relevance of CDW management within the project's financial framework.

2.2 Experimental Data Collection

An experimental approach was implemented based on the systematic collection of on-site data throughout the entire construction process, from initial earthworks to completion. This continuous monitoring enabled a detailed and temporally resolved characterization of construction and demolition waste (CDW) generation at project level (Fig. 1).

The primary sources of information were:

- waste dispatch records, documenting each removal event, the type of container used, declared waste type, and estimated or measured volume;
- certificates issued by authorized treatment facilities, specifying the mass of waste received, the corresponding European Waste Catalogue (EWC/LER) codes, and the final treatment option;
- construction progress certifications, which provided a reliable record of executed work, allowing the allocation of waste flows to specific construction stages and work packages.

These datasets were cross-checked and harmonized to obtain consistent, project-wide waste balances. The combination of volumetric information from dispatch records and gravimetric data from facility certificates enabled the quantification of actual CDW in both mass and volume, and the derivation of effective material density coefficients for each waste fraction. All recorded flows were classified according to EWC/LER codes, and assigned to specific management routes (on-site reuse, off-site recycling, recovery, or landfill disposal).

Finally, unit costs reported in the treatment certificates and transport invoices were used to calculate the economic costs associated with each waste stream. These were then aggregated and related to the construction budget (PEM), allowing assessment of the budgetary impact of CDW management and comparison with the cost assumptions made in the project's waste management planning documents.



Fig. 1. Vallecas Construction Site (VA001). From left to right: Construction and Demolition Waste (CDW) plasterboard; Non-hazardous mix Level II CDW. Non-stony nature; Hazardous CDW.

2.3 Data Analysis and Comparison

Experimental results were systematically compared with estimates derived from EGR and PGR methods, as well as across the project sample, to evaluate the role of construction typology in CDW generation. The comparison exposed noteworthy divergences and underscored structural limitations of current estimation techniques.

3 Results and Discussion

The calculation of the construction and demolition waste (CDW) footprint provided quantitative evidence of substantial discrepancies between theoretical estimations and observed on-site waste generation at project level (Table 1). These deviations were detected for both non-hazardous and hazardous waste streams, revealing structural limitations in current estimation practices embedded in regulatory planning instruments.

For non-hazardous CDW, the comparison between design-stage documents and measured data showed that the Waste Management Study (EGR) systematically underestimates the total amount of waste generated by approximately 18%. The deviation is even larger for the Waste Management Plan (PGR), which underestimates non-hazardous CDW by up to 27%. Given that both EGR and PGR are mandatory, standardized tools

in the current regulatory framework, these results indicate that they do not adequately reflect real on-site conditions and may lead to insufficient dimensioning of downstream management infrastructure and budgets.

In contrast, for hazardous CDW, the mismatch presents an opposite pattern. Here, the theoretical estimations included in EGR and PGR grossly overestimate the quantities actually generated. Estimated hazardous waste quantities exceed measured values by factors of approximately 400 (EGR) and 900 (PGR), respectively. This overestimation suggests an overly conservative or poorly calibrated approach to hazardous waste forecasting, with potential implications for cost allocation, contracting of specialized treatment services, and the interpretation of compliance with legal thresholds. Together, these findings underscore the need to revise and recalibrate current CDW estimation methodologies to improve their accuracy and reliability.

Table 1. Total CDW estimates versus actual CDW generation.

	EGR	PGR
Non-hazardous CDW	−18% vs. actual	−27% vs. actual
Hazardous CDW	400× actual	900× actual

This systematic overestimation suggests a conservative approach in project documentation, likely driven by regulatory compliance requirements, but it also evidences a lack of precision in forecasting hazardous waste streams.

With respect to Level I waste (uncontaminated soil and inert materials), the CDW footprint is strongly influenced by building configuration, particularly the number of underground levels. The results indicate specific generation rates of 3.83 m^3/m^2 of below-ground built area for buildings with one basement and 4.60 m^3/m^2 for those with two basements. These findings confirm that excavation volume is the primary driver of Level I waste generation, rather than the construction methodology employed (Table 2).

Table 2. Level I waste footprint.

	CDW Footprint Level I (m^3/m^2 B/R)
One basement	3.83
Two basements	4.60

In contrast, Level II waste (including both inert and non-inert fractions) exhibits a clear dependence on construction typology. In buildings executed using conventional construction techniques, the CDW footprint attains 0.50 m^3/m^2 of above-ground built area, whereas this value decreases markedly to 0.30 m^3/m^2 in projects that incorporate prefabricated or industrialized systems (Table 3). This reduction provides quantitative evidence of the effectiveness of construction industrialization strategies in reducing waste generation during the execution phase.

Table 3. Level II waste footprint.

	CDW Footprint Level II non-hazardous (m^3/m^2 S/R)
Traditional	0.50
Industrialized	0.30

A comparable pattern is observed for hazardous Level II waste, although with much lower absolute values. Owing to the absence of reliable volumetric data, these waste streams were quantified exclusively in mass terms. The results indicate a hazardous Level II CDW footprint of 0.000075 t/m^2 for buildings constructed using traditional methods and 0.000046 t/m^2 for projects employing industrialized construction systems (Table 4). Although their contribution to total waste generation is relatively minor, the reduction associated with industrialized processes is consistent with the trends identified for non-hazardous waste, thereby reinforcing the positive influence of construction industrialization on overall waste minimization.

Table 4. Hazardous Level II CDW (mass).

	CDW Footprint Level II hazardous (t/m^2 S/R)
Traditional	0.000075
Industrialized	0.000046

The observed differences are also evident in the economic assessment of CDW management. The results indicate that a higher degree of industrialization leads to a substantial reduction in waste management costs, particularly for Level II inert and hazardous fractions. In the case studies analyzed, savings of approximately €35,700 were recorded for Level II inert waste and €850 for hazardous waste, corresponding to an overall cost reduction of around 20% in the more industrialized project. By contrast, the costs associated with Level I waste and non-inert Level II waste were not significantly affected by construction typology but were instead primarily governed by the volume of excavation.

Overall, the results show that current estimation tools (EGR and PGR) exhibit notable limitations in accurately predicting CDW generation, especially for hazardous waste. Moreover, the findings confirm that construction typology and the degree of industrialization are key determinants of both waste generation and management costs. These insights highlight the need to integrate real on-site data into estimation models and support the adoption of industrialized construction systems as an effective strategy to reduce both environmental impacts and economic costs (Table 5).

These results confirm that the current estimation tools (EGR and PGR) present notable limitations, particularly in the case of hazardous waste. The findings indicate that construction typology and the degree of industrialization are key determinants of both waste generation and associated management costs. Specifically, industrialized

Table 5. Economic assessment.

	Economic savings on total CDW management
Traditional	0%
Industrialized	20%

construction methods substantially reduce material waste, enhance the efficiency of recycling processes, and yield significant economic savings. Overall, these outcomes support the implementation of industrialized systems as an effective strategy to advance circular economy objectives in the construction sector.

4 Conclusions

This study provides a comprehensive assessment of construction and demolition waste (CDW) management within the current regulatory framework. Recent regulations are broadly aligned with European waste management targets; however, their implementation is still at an early stage and will require long-term, region-specific strategies to become fully effective. The findings highlight that digitalization is essential to ensure traceability and operational efficiency across the CDW value chain, and that strict compliance with Law 7/2022 (Spanish Law) is particularly critical for both transporters and waste managers.

Pre-construction review of the Waste Management Study (EGR) and Waste Management Plan (PGR) contributes to more accurate planning and improved stakeholder compliance, while training and awareness-raising activities are shown to enhance appropriate on-site waste management practices. During the construction phase, systematic verification of documentation helps maintain traceability, although a tendency to simplify European Waste Catalogue (EWC/LER) codes is observed in practice. In terms of waste streams, Level I waste (primarily uncontaminated soil and inert materials) predominates in the early project stages, whereas Level II waste increases significantly during the masonry phase. Circular economy practices, such as the reuse of excavated soil, are only partially implemented. Hazardous waste generation is substantially lower than initially estimated, and recycling routes prevail over final disposal.

The results confirm that industrialized construction systems reduce both total waste generation and associated CDW management costs by up to 20%. Overall, progress towards a circular economy in the construction sector depends on the combined effect of regulatory compliance, digitalization, active stakeholder engagement, and the adoption of industrialized processes. Under these conditions, the construction sector can play a decisive role in achieving broader environmental and sustainability objectives.

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Tracing Circularity in Construction: A Multi-Level NLP Analysis of Theory, Policy, and Practice

Aidana Tleuken[1,3(✉)] and Rand Askar[2]

[1] Department Industrial Engineering and Business Information Systems, University of Twente, Enschede, Netherlands
a.tleuken@utwente.nl

[2] ISISE, ARISE, Department of Civil Engineering, University of Minho, 4804-533 Guimarães, Portugal

[3] Department of Civil Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Astana, Kazakhstan

Abstract. Despite the urgency to transition to a Circular Economy (CE) in construction, circularity principles remain inconsistently implemented and difficult to monitor across stakeholders and regulatory contexts. This study employs Natural Language Processing (NLP) to examine how circular construction is defined, debated, and operationalised across multiple levels and discourses. A multi-level analysis (academic, social media, regulatory levels) is introduced to trace how circularity concepts travel from theory to practice. At the academic level, NLP analysis of 480 articles reveals a conceptual divergence between circularity objectives focused on operational resource efficiency and waste management, and broader sustainability objectives addressing long-term environmental impacts. This conceptual ambiguity can hinder coherent implementation. At the public-discourse level, sentiment analysis shows that 57% of stake-holder opinions on construction circularity are positive, highlighting which concepts resonate and which remain abstract. At the policy level, analysis of CE strategies from 57 countries identifies five implementation clusters based on the 10R hierarchy, demonstrating that adoption patterns are shaped more by institutional capacity than economic development. At the technical level, text-mining of standards in Central Asia shows that many CE principles promoted in academia and policy fail to materialise in operational requirements. This multi-level approach reveals three critical dynamics: (1) vertical disconnects between policy ambitions and technical standards; (2) horizontal variation in national interpretations of circularity; and (3) missing feedback loops between implementation challenges and strategic or research agendas. NLP provides a diagnostic tool enabling stakeholders to identify misalignments and understand how circularity concepts diffuse—or stall—across the construction ecosystem.

Keywords: Artificial Intelligence · Natural Language Processing · Circular Construction · Sentiment Analysis · Circular Economy Policy

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1 Introduction

The buildings and construction sector is a major driver of resource use, emissions, and waste. Recent global reporting shows that the sector consumes a large share of energy and contributes significantly to global CO_2 emissions, while relying heavily on materials such as cement and steel that are also major sources of environmental impact (UNEP, 2025). Circular economy (CE) strategies aim to reduce these impacts by extending material lifetimes, keeping value in use, and reducing demand for virgin resources. Despite growing research and policy attention, global circularity is declining: the share of secondary materials in the global economy fell from 9.1% in 2018 to 7.2% in 2023 (CEF, 2024). In construction, this gap is often attributed to fragmented supply chains, unclear responsibilities, and limited incentives. However, these explanations do not fully explain why well-established CE concepts rarely translate to practical and enforceable requirements in day-to-day delivery.

This paper frames the problem as a knowledge translation challenge. In many fields, the movement from research evidence to action is treated as a process with identifiable stages and potential failure points (Graham et al., 2006). In circular construction, ideas typically emerge in research, get interpreted in professional and public discourse, become priorities in policy frameworks, and finally appear as requirements in technical standards and codes. If concepts lose clarity, priority, or enforceability along this chain, implementation remains slow even when the research base is strong.

Computational tools for analysing these processes have advanced rapidly. Natural language processing (NLP) and large language models (LLMs) are increasingly used to extract and structure information from large textual datasets, including policy and regulatory documents. However, most studies still focus on a single level of discourse at a time, such as academic literature (e.g. Aubakirov et al., 2025), stakeholder perceptions (e.g. Tleuken et al., 2024; Karaca et al., 2024), policy studies, or technical regulations (e.g. Tleuken et al., n.d.-b), limiting their ability to explain the implementation gap, which emerges across levels.

To address this limitation, this paper proposes a multi-level diagnostic framework linking four discourse levels: academic literature (Aubakirov et al., 2025), public (Tleuken et al., 2024) and professional (Karaca et al., 2024) discourse, policy documents (Tleuken et al., n.d.-a), and technical standards (Tleuken et al., n.d.-b). Using the 10R hierarchy of circularity strategies as a shared taxonomy, the framework analyses how CE concepts evolve across these levels. Drawing on recent NLP- and LLM-based analyses conducted in these studies, the framework offers a connected evidence base that shows where CE concepts weaken, diverge between contexts, or fail to convert into enforceable technical provisions.

2 Methods

This paper synthesises four prior studies by the authors and collaborators, each applying NLP to a different discourse level in circular construction. Study-specific data collection and validation procedures are detailed in the original publications and summarised here briefly. The main contribution is the cross-level comparison procedure in Sect. 2.1,

which integrates the findings using a shared 10R taxonomy. This section describes the data sources, NLP techniques, and analytical procedures applied at each level of the framework. Because the individual level analyses have been or are being reported in dedicated publications, the methods are presented concisely and readers are referred to those studies for full technical detail. The cross-level comparison method, which is new to this paper, is described in greater depth.

Level 1: Academic Discourse 480 review articles (2021–2024) from Scopus were analysed: 107 on circular construction and 373 on sustainable construction. Three NLP techniques (TF-IDF, TextRank, and Named Entity Recognition) identified distinctive terms and concept clusters, distinguishing circular from sustainable construction vocabulary. Full details in Aubakirov et al. (2025).

Level 2: Public and Professional Discourse Two datasets were used. First, 906 text chunks from seven online platforms were analysed using sentiment analysis (fine-tuned MPNet, F1 = 0.68) and topic modelling, yielding eight discourse topics (Tleuken et al., 2024). Second, a survey of 382 stakeholders across seven countries assessed perceptions of circular construction costs and benefits, with XGBoost and SHAP used to identify key influencing factors (Karaca et al., 2024).

Level 3: Policy Discourse CE strategy documents from 57 countries were analysed using the 10R hierarchy, classifying policy content by R-strategy emphasis. Cluster analysis identified five country implementation profiles. Full details in Tleuken et al. (n.d.-a).

Level 4: Technical Standards 165 Kazakhstani construction norms (SNiP) were analysed in Russian using a hybrid human-machine workflow. DeepSeek V3 identified relevant segments, which were manually validated to produce 519 confirmed provisions, each coded by 10R principle, normative strength, and enforcement mechanism. Sentence-BERT embeddings and PCA were used for semantic analysis. Full details in Tleuken et al. (n.d.-b).

2.1 Cross-Level Comparison

The cross-level comparison is the methodological contribution of this paper. First, findings from all four levels were mapped onto the 10R hierarchy as a shared taxonomy (Kirchherr et al., 2018). For Levels 3 and 4, the mapping is direct as the original analyses already use the 10R framework. For Levels 1 and 2, key terms and topics were interpreted and assigned to corresponding strategies (e.g. "design-for-disassembly" maps to Rethink; "waste diversion" maps to Recycle/Recover). Second, the mapped findings were analysed using a gap-identification protocol to detect three patterns: (a) vertical disconnects, where a principle's presence drops sharply between adjacent levels; (b) horizontal variations, where the same principle is emphasised differently across countries at the policy level; and (c) missing feedback loops, where challenges identified at Levels 2 or 4 do not appear to inform the agendas at Levels 1 or 3. Interpretive judgement is required when mapping Levels 1 and 2 to the 10R taxonomy. Both authors independently assigned terms and topics to R-strategies, resolving disagreements through discussion and assigning borderline cases to the more conservative (lower-order R) category.

3 Results

3.1 Levels Overview

Level 1: Academic Discourse Analysis of 480 review articles reveals a clear conceptual split. Circular construction centres on resource efficiency, waste management, and material lifecycle strategies, while sustainable construction is broader, encompassing urban planning, energy performance, and social dimensions. Although often used interchangeably, circular construction focuses on closing material loops whereas sustainable construction addresses wider environmental and social outcomes. This conceptual confusion at the academic level creates a shaky foundation for the levels that follow.

Level 2: Public Discourse Public attitudes are moderately positive (57% positive, 28% neutral, 15% negative). Positive sentiment clusters around innovation and environmental benefits; negative sentiment around cost, implementation difficulty, and feasibility concerns. Stakeholders in countries with stronger CE policy frameworks report more positive expectations. Notably, technical concepts common in academic literature, such as design-for-disassembly or material passports, barely appear in public discourse.

Level 3: Policy Discourse Analysis of CE strategy documents from 57 countries identifies five implementation clusters ranging from downstream revalorisation to upstream life-extension strategies. Cluster membership is shaped more by institutional capacity and regulatory maturity than by GDP. Most countries gravitate toward recycling and recovery as the most accessible entry point, while higher-order strategies like Refuse or Rethink appear mainly in countries with established environmental governance.

Level 4: Technical Standards 519 coded provisions from 165 Kazakhstani construction norms show an uneven distribution across the 10R framework. Reduce dominates ($\approx$150 provisions), while Repurpose, Recover, Refuse, and Remanufacture are weakly represented. Most provisions are recommendatory rather than mandatory, with enforcement mechanisms largely absent, and higher-order circular strategies linguistically dispersed across regulatory texts.

3.2 Cross-Level Synthesis

Cross-level analysis represented in Table 1 reveals three main dynamics:

- Vertical disconnects. Circular strategies widely discussed in academic and policy discourse, such as Refuse, Remanufacture, and Repurpose, are largely absent from technical standards or appear only as non-binding recommendations.
- Horizontal Variation. Policy strategies vary significantly across countries. Differences are shaped primarily by institutional capacity and regulatory traditions rather than economic development level.
- Missing feedback loops. Implementation challenges identified in public dis-course and technical standards, such as cost concerns or enforcement gaps, do not appear to influence academic research agendas or policy design. The knowledge translation process therefore operates largely in a top-down direction.

Table 1. Cross-level concept tracing matrix using the 10R hierarchy.

10R	Level 1: Academic	Level 2: Public	Level 3: Policy	Level 4: Standards
Refuse	Weak–Moderate. Prevention focus; limited operational definition.	Absent.	Variable. Present in "Pre-ventive" cluster countries only.	Weak. <35 clauses; no enforcement.
Rethink	Strong. Design-for-disassembly, modularity.	Absent–Weak. Expert vocabulary doesn't transfer.	Moderate. Preventive and upstream clusters.	Moderate. ~80 clauses; mostly advisory.
Reduce	Strong. Core concept; overlaps with sustainable construction.	Moderate. Efficiency and cost narratives.	Strong. Common entry-point across clusters.	Strong. ~150 clauses; highest mandatory share, but little enforcement.
Reuse	Strong. Material lifecycle reuse.	Weak–Moderate. Practical examples resonate.	Moderate–Strong. Life-extension clusters.	Moderate. ~65 clauses; mostly advisory.
Repair	Moderate. Life extension and maintenance.	Weak. Framed as maintenance, not circularity.	Variable. Some prevention-oriented contexts.	Moderate. 40–50 clauses; only principle with meaningful enforcement (~25%).
Re-furbish	Moderate. Renovation and retrofit.	Weak–Moderate. Re-novation narratives.	Moderate. Downstream life-extension cluster.	Moderate. 40–50 clauses; technical execution partly mandatory.
Remanufacture	Weak. Limited in construction.	Absent.	Weak. Advanced industrial policy countries only.	Absent–Weak. Virtually absent; no enforcement.
Repurpose	Weak. Niche; demolition materials.	Absent.	Weak. Low emphasis across clusters.	Weak. ~15 clauses; advisory only.
Recycle	Strong. Default circular strategy.	Moderate. Waste management framing.	Strong. Central in revalorisation clusters.	Moderate. 40–50 clauses; no binding targets.

(*continued*)

Table 1. (*continued*)

10R	Level 1: Academic	Level 2: Public	Level 3: Policy	Level 4: Standards
Recover	Weak. Lowest-priority in academic framing.	Absent–Weak.	Moderate. Back-up strategy in down-stream revalorisation.	Weak. <35 clauses; advisory only.

4 Discussion

This paper links four discourse levels to examine why CE ideas in construction of-ten remain aspirational. The same pattern appears across all four: concepts are well developed in research, partially echoed in policy, weakly represented in public dis-course, and only selectively binding in technical standards, consistent with a "translation chain" interpretation where failure occurs at interfaces between communities and institutions (Graham et al., 2006). This complements existing barrier research: while cost, fragmented responsibilities, and limited incentives are well documented, they do not explain why clear concepts still fail to become enforceable requirements. Our results point to weak conversion from concepts into standardised, enforceable language as a key underlying mechanism.

Vertical disconnects: ideas weaken on the way to standards: The clearest result is vertical attenuation: higher-order CE strategies prominent in research and policy weaken sharply in technical standards, where CE-related provisions are often advisory and rarely paired with compliance checks. Design-for-disassembly illustrates this pattern, common in research as an enabling concept for reuse and adaptability, yet difficult to translate into specific, measurable, and enforceable standard clauses. Similarly, material and product passports are widely discussed as traceability tools but depend on data governance and interoperability practices not automatically present in standards systems. When strategies lose specificity and binding force as they move downward, implementation remains uneven even where policy ambition exists.

Horizontal variation: policy pathways depend on institutions, not only income. The policy clustering shows that countries do not converge on a single CE pathway. Different national profiles emphasise different parts of the 10R hierarchy, and many countries prioritise downstream or lower-risk strategies first. This aligns with broader evidence that CE progress depends strongly on institutional, cultural, and governance conditions rather than technology alone (Kirchherr et al., 2018). It also matches construction-specific policy research arguing that CE policy is often fragmented across instruments and stages, with limited integrated frameworks that link strategy to delivery mechanisms. Our contribution is to connect this variation to what becomes codified. A strategy can be present in policy language yet remain weak in standards if enforcement capacity, administrative routines, or market infrastructure are missing. This suggests that policy ambition is not a reliable proxy for implementation readiness. A more useful indicator is whether a country can translate CE priorities into clauses that specify responsibilities, verification, and consequences for non-compliance.

Missing feedback loops: practice signals do not correct upstream agendas. A third result is the weak upward flow of information. Public discourse and survey responses emphasise feasibility, cost burdens, and responsibility gaps. Standards analysis shows limited enforcement language and limited coverage of higher-order strategies. Yet these signals do not clearly reappear as corrective inputs in academic framing or policy priorities. This resonates with critiques that CE can become concept-heavy and politically convenient, while structural constraints and power dynamics remain under-addressed (Corvellec et al., 2022). From a knowledge translation perspective, feed-back is not optional. Iteration is central to moving from evidence to sustained practice (Graham et al., 2006). In a construction context, this means that the standards revision process, procurement feedback, compliance outcomes, and observed implementation failures should be visible upstream and should shape both research agendas and policy design. Our results suggest that these feedback channels are weak or informal, which contributes to repetition of well-known "barriers" without corresponding improvement in codification and enforcement.

Three implications follow. First, advisory language is insufficient for CE outcomes requiring coordinated action: standards need more measurable, verifiable clauses, particularly for higher-order strategies dependent on early design decisions. Second, policy design should match institutional capacity: the risk is not that countries follow different CE sequences, but that policy language is imported without the governance mechanisms to implement it. Third, standards revision should be formally linked to compliance evidence and practical constraints, and shared with researchers and policymakers. Without this, CE remains aspirational rather than corrected by implementation reality. Methodologically, the main contribution is the comparative design: a shared taxonomy across discourse levels combined with text-based evidence of attenuation, variation, and missing feedback. LLM-assisted extraction is valuable for large regulatory corpora, but the goal remains governance insight, identifying what be-comes binding, what is verifiable, and what is left as suggestion.

5 Conclusions

This paper presented a multi-level diagnostic framework examining how CE ideas in construction move from concept to practice, linking academic literature, public discourse, policy documents, and technical standards through a shared 10R taxonomy. Three key findings emerge. First, higher-order CE strategies visible in research and policy are weakly represented in technical standards, often appearing as recommendations rather than mandatory provisions. Second, countries cluster into distinct CE strategy profiles, reflecting differences in institutional capacity and regulatory tradition. Third, feedback loops are weak – feasibility and cost concerns raised in public discourse do not consistently inform research agendas or policy design. The frame-work has practical implications: policymakers should ensure CE priorities translate into specific, verifiable, and enforceable clauses; industry can distinguish binding rules from voluntary guidance; and researchers should study translation mechanisms more directly. Limitations include geographic and temporal variation across levels and a single-country standards analysis. Future work should extend the analysis to additional contexts and test whether translation patterns hold in other regulatory environments. Overall, the framework makes

translation gaps visible, supports targeted interventions, and emphasizes stronger links between research, policy, and practice.

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What Stakeholders Expect from Innovative Construction Solutions

Spyridon Karytsas[1], Dimitrios Mendrinos[1(✉)], Theoni I. Oikonomou[1], Constantine Karytsas[1], Carlos L. Rodríguez López[2], Miriam Hernández Pérez[2], and Irene Beleña Pozo[3]

[1] Division for Renewable Energy Technologies, Centre for Renewable Energy Sources and Saving, Pikermi, Greece
dmendrin@cres.gr

[2] Department of Sustainable Construction, Centro Tecnológico de la Construcción de la Región de Murcia, Alcantarilla, Spain

[3] AIDIMME Instituto Tecnológico, Paterna, Spain

Abstract. This paper investigates end-user expectations regarding building thermal insulation materials through a multi-stakeholder survey of 115 respondents across 12 European countries, complemented by statistical analysis and validation with industry manufacturers. The research methodology comprised a literature review of end-user preferences, conceptual model development, survey design, statistical analysis using the Kruskal-Wallis nonparametric test, and a two-phase manufacturer validation. Survey results demonstrate that end-users maintain a functional approach to insulation material selection, prioritizing specifications that deliver tangible, measurable benefits, with a strong emphasis on health and safety considerations, thermal performance, durability, moisture resistance and energy efficiency and relatively low importance assigned to aesthetics and sustainability credentials. The end-user behavior hierarchy ranks technical factors as the most important, followed by economic, environmental, and, lastly, social considerations, a ranking confirmed independently by industry manufacturers. Critically, a sustainability gap is identified: current preferences for environmental specifications remain substantially below levels implied by EU policy goals, yet higher-knowledge respondents show significantly greater appreciation for sustainability criteria, suggesting that education and regulation will progressively reshape market priorities. The manufacturers' validation identified durability demonstration, moisture resistance, cost competitiveness, and communication as critical development challenges for innovative materials, defining the frontier where material innovation must meet market requirements to enable widespread adoption of sustainable construction solutions.

Keywords: Thermal insulation · Construction material · Specification · User needs

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1 Introduction

The transition towards sustainable built environments requires a deep understanding of end-user expectations regarding construction materials, particularly thermal insulation. Despite the proliferation of innovative insulation solutions, including bio-based, recycled, and high-performance aerogel materials, their market uptake remains constrained by complex socio-technical factors extending beyond technical performance alone [1, 5, 16]. While individual studies have examined specific stakeholder groups or national contexts, no prior work has systematically quantified preference hierarchies across multiple end-user categories and diverse European geographies simultaneously, nor triangulated those preferences against manufacturer market experience.

Existing research has explored barriers and drivers for energy-efficient technologies from various perspectives [3, 4, 11], but systematic quantitative assessments integrating multiple end-user categories across diverse European contexts remain limited. This paper addresses this gap through a comprehensive multi-stakeholder survey conducted within the SNUG European project (https://snugproject.eu/), targeting 115 end-users from 12 European countries, validated through direct engagement with building component manufacturers. The study examines which material specifications end users prioritize, how decision-making varies by expertise level, and the implications for developing and positioning innovative, sustainable insulation solutions.

2 Theoretical Framework

A literature review established the conceptual foundation for the study, synthesizing two streams: technical assessments of insulation material properties [1, 6] and socio-behavioral studies examining barriers and drivers affecting innovative material adoption [2–5, 7–16]. Jelle [1] identified critical insulation properties including thermal conductivity, fire protection, water resistance, and climate-aging durability. Schiavoni et al. [6] conducted a comparative analysis across commercialized materials on thermal performance, acoustic properties, environmental impact, and vapor resistance. On the adoption side, Camarasa et al. [11] found that technical and economic drivers have the greatest potential to promote energy-efficient technologies, while economic barriers remain the primary impediment. Studies on bio-based and circular materials [5, 13, 16] identify inadequate incentives, insufficient knowledge, performance concerns, and supply chain immaturity as significant barriers. Regulatory frameworks consistently emerge as dual-role factors [3, 12, 15], while Tsoka et al. [7] highlighted that investment costs, maintenance issues, and low professional knowledge levels are the main constraints to technology diffusion in Mediterranean contexts.

The conceptual model (Fig. 1) synthesizes these findings by mapping insulation specifications to key driver and barrier categories: technical, economic, environmental, social, and regulatory. This framework guided both survey instrument development and results interpretation.

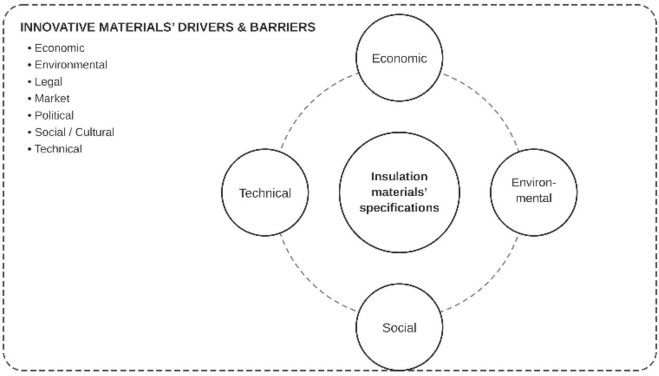


Fig. 1. Literature-based conceptual model that represents insulation material specifications together with market drivers and barriers influencing innovative material adoption.

3 Materials and Methods

3.1 Survey Design and Instrument

An online questionnaire, "Desired properties of buildings' thermal insulation", was developed on the Google Forms platform and distributed in English. Based on the conceptual model, the survey assessed 35 insulation material specifications. Respondents rated each specification on a five-point Likert scale from "not important" to "very important," and additionally selected their top three most important specifications. Background sections collected data on respondent category, country of origin, and self-assessed knowledge level of insulation materials.

3.2 Stakeholder Categories and Sampling

Thirteen end-user categories were defined through a dedicated SNUG project workshop: architects, planners and engineers; building occupants; building owners; building and construction companies; energy consultants; facility managers; certification providers; financing organizations; professional organizations; property managers; public authorities; real estate agents; and associations of building component manufacturers. A total of 115 responses were collected during March 2024 from 12 European countries. Spain (20%), Austria (16%), Greece (13%), and Portugal (12%) had the highest participation. Architects, planners and engineers constituted the largest group (28%), followed by building occupants (15%) and private building owners (11%). Approximately 40% of respondents self-assessed their knowledge as high, 40% as average, and 20% as low. Sampling was coordinated through SNUG project partner networks (minimum ten respondents per country), a convenience approach that over-represents southern and central European professional networks; findings should therefore be interpreted as indicative of practitioner-weighted European preferences rather than a fully representative population sample.

3.3 Statistical Analysis

Statistical analysis was performed using SPSS 20. Descriptive statistics characterized overall importance ratings. Given the ordinal nature of Likert-scale responses, nonparametric Kruskal-Wallis H tests were applied to compare importance ratings across the three knowledge-level groups (low, average, high), with pairwise post hoc tests for comparisons that showed statistically significant differences ($p < 0.05$). Top-3 specification selections and the four-criteria ranking question (technical, economic, environmental, social) were analyzed using frequency distributions.

3.4 Manufacturer Validation

Survey findings were validated through a structured questionnaire distributed to five building component manufacturers participating in the SNUG consortium during September–October 2025, followed by a dedicated online workshop on 8 October 2025 with six participants from four partner organizations. This two-phase validation methodology enabled both individual written reflection and collective discussion of discrepancies between survey findings and market experience.

4 Results

4.1 Overall Specification Importance Rankings

The survey results reveal a clear hierarchy in how end-users prioritize insulation material specifications. Impact on human health led all specifications with 70% of respondents rating it "very important," followed by release of dangerous substances (68%), durability (67%), energy efficiency (67%), thermal conductivity/thermal insulation performance (63%), thermal comfort (60%), resistance to fire (59%), fume emission during fire (57%), and water/vapor resistance (54%). The overall ranking of selection criteria placed technical factors first, followed by economic, environmental, and social considerations.

Conversely, the least important specifications were weight/density (15% very important), aesthetics (17%), bio-based material (18%), and biodegradable material (23%). Notably, cost efficiency/payback period (52% very important) ranked ninth in mean importance values yet emerged as the most frequently selected top-3 specification (11.5% of responses), suggesting that cost operates as a threshold criterion rather than a simple ranking factor in end-user decision-making.

4.2 Knowledge-Level Differences

Kruskal-Wallis H tests revealed statistically significant differences ($p < 0.05$) between knowledge-level groups for six specifications: aesthetics ($p = 0.004$), biodegradable material ($p = 0.026$), recyclability and reusability ($p = 0.000$), supply security ($p = 0.031$), sustainability ($p = 0.028$), and thermal conductivity/thermal insulation performance ($p = 0.031$). Low-knowledge respondents assigned significantly lower importance to biodegradability, recyclability and reusability, supply security, sustainability, and

thermal conductivity than average- or high-knowledge groups. High-knowledge respondents rated aesthetics as significantly less important than the other two groups. Energy efficiency and impact on human health were consistently ranked in the top four across all groups; weight/density and bio-based material remained among the four least important, indicating broad cross-segment consensus on these anchor specifications. From a stakeholder-type perspective, architects, planners and engineers (28%) likely drive the performance-first orientation through code-compliance obligations, while building occupants (15%) reinforce the prominence of health and comfort specifications. The convergence of these groups on the same top-ranked specifications provides robust cross-stakeholder validation of the overall hierarchy.

5 Manufacturer Validation

5.1 Alignment with Market Experience

Manufacturer validation confirmed strong overall alignment between survey findings and market experience. All five participating manufacturers confirmed that the top-ranked specifications (health impact, energy efficiency, durability, thermal conductivity, and fire resistance) accurately reflect customer priorities. Customers typically establish baseline requirements for health, fire safety, and performance before considering economic factors; price and payback become relevant only after these thresholds are met. The criteria hierarchy (technical > economic > environmental > social) was explicitly confirmed by multiple manufacturer partners.

5.2 Contradictions and Discrepancies

Despite overall alignment, manufacturers identified important discrepancies. Cost efficiency carries more weight in actual purchasing decisions than survey rankings suggest, particularly in certain industry sectors. The low ranking of sustainability specifications, especially recyclability and reusability, surprised several manufacturers who observe increasing demand for circular and bio-based solutions in public procurement contexts, revealing a temporal gap between current stated preferences and emerging requirements driven by regulatory pressure and ESG considerations. While lead time appeared unimportant in the survey, manufacturers noted that supply reliability is often decisive in actual projects.

5.3 Development Challenges and Communication Barriers

Manufacturers identified four critical development challenges for innovative insulation materials: demonstrating proven long-term durability (new circular materials lack the field validation of traditional alternatives); achieving moisture resistance comparable to conventional materials; developing cost-competitive production and supply chains; and communicating complex technical benefits, including embodied carbon and durability metrics, to varied audiences. Manufacturers described segmented strategies, from detailed datasheets and LCAs for high-knowledge professionals to comfort, health, and payback messaging for general end-users.

6 Discussion

6.1 Functional Market Orientation

End-users approach insulation selection with a strongly functional orientation, prioritizing measurable performance over aesthetic or abstract sustainability credentials. This aligns with McCoy et al. [2], who identified relative advantage and risk reduction as the primary adoption drivers, and with Camarasa et al. [11], who found that technical and economic drivers have the highest promotion potential across EU markets. The causal mechanism is rooted in risk-aversion and accountability: professional specifiers face regulatory, liability, and warranty obligations that reward proven, certifiable performance, creating institutional incentives that amplify the perceived importance of health, safety, and technical compliance. Sustainability specifications lack equivalent mandatory enforcement mechanisms at the point of specification, relegating them to secondary consideration, suggesting that health-positive framing offers bio-based insulation developers a more effective market-entry strategy than environmental credentials alone.

6.2 The Cost Paradox

The contradiction between cost efficiency ranking ninth in mean importance yet emerging as the top specification in top-3 selections suggests that cost functions as a qualifying threshold rather than a differentiating criterion: materials must be cost-competitive to remain in consideration, after which technical performance and health and safety determine final selection. This two-stage decision architecture is consistent with behavioral economics frameworks where threshold satisficing precedes optimization. As Markström et al. [5] note, inadequate incentives and high costs remain primary barriers for bio-based materials, confirming that cost parity is a critical precondition for market entry.

6.3 Sustainability Gap and Market Evolution

The low importance assigned to sustainability specifications (recyclability: 30%; bio-based: 18%; biodegradable: 23%) contrasts sharply with growing EU regulatory emphasis on circular-economy principles and embodied carbon. Directives such as the EPBD and the Construction Products Regulation are progressively mandating embodied carbon accounting and circular material flows, creating a structural divergence between current preferences and emerging requirements. This gap mirrors that of Gottlieb et al. [16], who documented cultural, market, and institutional barriers hindering bio-based material adoption despite favorable regulatory intent and is sustained by the absence of mandatory sustainability specifications in procurement, limited market education, and the longer payback horizon for environmental benefits. However, higher expertise correlates significantly with greater appreciation for sustainability specifications ($p < 0.05$ for recyclability, biodegradability, and sustainability), indicating that education and tightening regulatory compliance will progressively close the gap. A phased strategy is therefore appropriate: establish performance credibility first, then highlight environmental co-benefits, and ultimately advocate for instruments that elevate sustainability specifications to threshold status.

6.4 Implications for Innovative Construction Solutions

Successful innovative construction solutions must achieve a multi-dimensional value proposition [7, 8]. Environmental credentials alone are insufficient; materials must first deliver competitive technical performance in line with the specifications, as end users prioritize health and safety, thermal performance, durability, and moisture resistance. This reinforces Wang et al. [8], who identified business-related, technical, and policy barriers as the three constraint categories for green building material deployment. The manufacturer validation identifies four critical gaps: cost competitiveness, proven long-term durability, moisture resistance, and supply chain maturity. Bridging the sustainability gap requires coordinated action across three domains: technical (demonstrating performance parity), market (differentiating communication by knowledge level and stakeholder type), and policy (advocating for procurement instruments that elevate sustainable specifications from desirable to mandatory).

7 Conclusions

This study provides a comprehensive evidence base for end-user expectations on thermal insulation materials, integrating a literature review, a multi-stakeholder survey of 115 respondents across 13 categories and 12 European countries, and a two-phase validation exercise with five SNUG project manufacturers. End-users maintain a performance-first approach: health and safety (human health: 70%; dangerous substances: 68%) and core performance specifications (durability: 67%; energy efficiency: 67%; thermal conductivity: 63%) dominate across all stakeholder categories, while aesthetic and bio-based credentials receive substantially lower ratings. The decision-making hierarchy of technical, economic, environmental and social factors was confirmed statistically and through manufacturer validation, with cost efficiency as a threshold precondition. Knowledge-level analysis ($p < 0.05$ for six specifications) shows that higher-knowledge respondents value sustainability, recyclability, biodegradability, and supply security significantly more, revealing that current preferences and EU policy goals are misaligned in a knowledge-mediated way, making education and regulatory mandates effective levers for accelerating the transition. The manufacturer validation identified proven durability, moisture resistance, cost-competitive supply chains, and technical communication as critical challenges, defining the development agenda for sustainable insulation materials.

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Earthen Building Culture: Participatory Workshops for the Dissemination and Innovation in Abruzzo (Italy)

Stefania De Gregorio(✉), Luciana Mastrolonardo, and Donatella Radogna

Department of Architecture, University "G.'D'Annunzio" Chieti-Pescara, Pescara, Italy
stefania.degregorio@unich.it

Abstract. Earthen construction represents a sustainable and biodegradable resource, offering significant potential for resilient architectural practices in the context of climate change and environmental degradation. In Abruzzo (Italy), traditional earthen techniques historically supported rural settlements and community-based self-construction. However, the progressive adoption of industrial materials over the last century has led to a profound loss of intangible knowledge associated with this heritage technology. Preserving and reactivating this knowledge is essential for promoting culturally rooted, compatible with environmental protection, low tech and low cost.

This research investigates the results derived from participatory workshops, as tools for reintroducing and disseminating traditional earthen building skills within contemporary communities. Through hands-on laboratories open to citizens and targeted sessions for university students, participants engaged with the properties of local soils, learned traditional *massone* fabrication methods, and explored how variations in mixture composition affect performance. These activities connected the material resource (earth) with its intangible counterpart (collective memory and craftsmanship) highlighting the dual heritage value of earthen construction.

The outcomes demonstrate that participatory knowledge-transmission processes can enhance public awareness of sustainable construction, support local supply-chain resilience, and contribute to the regeneration of community identity. By integrating education, cultural heritage, and material innovation, the study aligns with the goals of resilient and sustainable built environments: reducing environmental impacts, fostering territorial circularity, and strengthening social engagement in the transition toward more adaptive and culturally meaningful construction practices.

Keywords: Sustainable Materials · Local Circular Supply Chain · Participatory Architecture · Traditional Building Culture

1 Introduction

Earthen construction represents one of the most ancient and widespread building techniques globally, experiencing renewed interest within contemporary sustainable architecture discourse [1]. Recent studies demonstrate that earthen materials require up to

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90% less energy and CO_2 than fired concrete or brick solutions [2, 3]. Earth as a building material is biodegradable, locally available, requires minimal energy for processing, and can be fully reintroduced in the environment at the end of its lifecycle [4]. Earth construction demonstrates low embodied energy, minimal CO2 emissions during production, complete recyclability, and biodegradability [5]. Earthen walls possess high thermal mass, moderating interior temperature fluctuations and creating comfortable indoor environments limiting the use of mechanical systems [6]. The material's hygroscopic properties enable passive humidity regulation, maintaining optimal moisture levels between 40–60% relative humidity, which contributes to occupant health and well-being [7]. Traditional earthen construction techniques, particularly monolithic systems, demonstrate resilience to seismic events when properly designed [8]. In addition, earthen architecture embodies a cultural heritage, representing community-based construction traditions, collective knowledge systems, and place-based identity [9]. Despite considerable advantages, earthen construction faces technical limitations that have contributed to its progressive disuse, resulted in profound progressive loss of craft knowledge [10]. In fact, earth materials are vulnerable to water erosion and moisture damage [11]. Compressive strength of unstabilised earth typically ranges from 0.5 to 3 MPa, significantly lower than fired brick (10–30 MPa) or concrete (20–50 MPa) [12]. Earth construction lacks comprehensive technical standards in many jurisdictions, creating uncertainties for designers, contractors, and building officials [13]. Given the sustainability of rammed earth constructions, necessary considering the high environmental impact of the construction sector,[1] international research is pushing towards process or product innovation in order to overcome the technical limitations described above. Addition of small quantities (5–15%) of hydraulic lime, natural pozzolans, or biopolymers enhances water resistance and compressive strength while maintaining environmental benefits [16]. Natural fibers from agricultural and industrial byproducts (straw, hemp, sisal, wood chips) significantly improve tensile strength, reduce shrinkage cracking, and enhance earthquake resistance [17]. Emerging technologies including 3D printing with earthen materials, robotic rammed earth compaction, and parametric formwork design enable precision construction with reduced labor requirements and improved quality control [18]. These innovations bridge traditional craft knowledge with contemporary construction logistics. Confirming the importance of this sustainable material, several countries have advanced earthen construction standards, including New Zealand's NZS 4298:2020 (Earth Buildings), Germany's DIN 18945–18947, and emerging Italian regional guidelines [19–22].

1.1 Abruzzo Earthen Architecture (Italy)

Abruzzo's earthen building tradition, documented since the Neolithic period, represents a continuous architectural lineage spanning millennia. The technique reached its apex during the 19th and early 20th centuries, when earthen structures served the agricultural economy [9, 10]. These structures utilized raw earth bricks or the *massone* technique,

[1] The construction sector currently accounts for nearly 34% (year 2023) of global carbon emissions [14], with cement production alone contributing 8% of annual greenhouse gas emissions [15].

distinctive to Abruzzo and Marche regions. The raw earth bricks or *massone* typically utilized 15–35% clay fraction, 20–40% silt, and 30–60% sand and gravel. Cereal straw (wheat, barley, or oat) constituted 3–6% of dry mass, 16–22% of water, providing tensile reinforcement and controlling desiccation cracking. In case of *massone*, the mixture was then hand-formed into loaves, weighing 5–10 kg each, roughly cylindrical with tapered ends, measuring 20–30 cm length and 15 cm diameter. These forms were rolled in additional straw to prevent adhesion during stacking and enhance overall tensile strength of the assembled wall. *Massoni* were stacked in continuous spiral courses 50–70 cm high, forming monolithic perimeter and partition walls simultaneously. Each course required 3–5 days drying before subsequent layer addition, during which builders trimmed and shaped walls to vertical alignment using specialized tools. The resulting walls exhibited characteristic tapering profile, ranging from 80–90 cm thickness at base to 50 cm at eaves [10, 23, 24]. In the Abruzzo region, thanks to the commitment of municipalities and cultural associations (such as the CED Terra in the municipality of Casalincontrada [24]), a process has been underway since 1993 to understand the location and state of maintenance of raw earth buildings, to recover the architectural heritage made of raw earth and to involve the community in its conservation. Systematic documentation conducted during 1985–2021 identified that while in 1930 in Abruzzo (Chieti and Pescara provinces) there were approximately n°7000 buildings made of raw earth, currently n°806 buildings made of raw earth have been registered, of which only n°91 are in a good state of conservation, spread out across the entire territory [24]. Building typologies include single-story agricultural shelters, residential dwellings, and occasional two-story structures incorporating ground-floor stables with upper living quarters. The decline in the number of rammed earth buildings and their state of conservation, due to the widespread use of "universally valid" materials such as concrete and steel, highlights how the cultural reactivation of rammed earth construction knowledge can connect environmental sustainability (it is a low environmental impact and km 0 material widely available), local memory (the memories of elderly people are still linked to the building forms related to this technology) and innovation (to overcome the durability limits of raw earth constructions).

2 Method

The research employed two workshop typologies designed to reach distinct audience segments while maintaining approaches centered on "learn by doing" (see Fig. 1). The first is a participatory workshop "for all" occurred during a public research dissemination event, utilizing an outdoor information and demonstration stand situated in a high-visibility urban location in Pescara (Italy). The stand operated continuously from 9:00–20:00, maximizing accessibility for spontaneous participation. Large-format educational panels communicated the cultural and technical significance of earthen construction in Abruzzo. Content of the panels addressed the environmental benefits of earthen materials; historical development of raw earth brick and *massone* technique; traditional construction processes; contemporary innovation potential; and comparison with conventional fired brick production. Visual documentation included historical photographs, architectural drawings, and lifecycle assessment diagrams illustrating carbon footprint

differentials. A hands-on *massone* and raw earth brick fabrication station enabled visitors to engage directly with material processes. Two expert facilitators staffed the demonstration area: a cultural heritage researcher, and a materials expert specialized in earthen mixture design. Completed specimens remained on display throughout the event, illustrating collective production and material characteristics during drying.

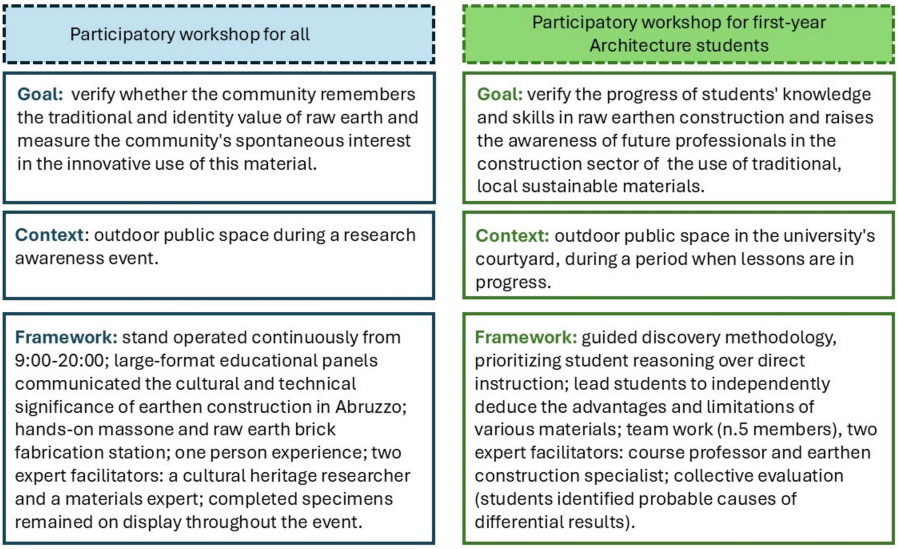


Fig. 1. Goal, context and framework of the 2 participatory workshops.

The second is a participatory workshop for first-year Architecture students at University "G. D'Annunzio" Chieti-Pescara, integrating earthen construction into fundamental building materials curriculum. The session occurred in the university's exterior courtyard, maintaining visibility to campus circulation, creating incidental awareness among broader university community. The workshop employed guided discovery methodology, prioritizing student reasoning over direct instruction. Initial discussion prompted students to articulate prior knowledge regarding construction materials, then introduced earthen techniques through comparative analysis with familiar materials (fired brick, concrete). Facilitated dialogue, coordinated between course professor and earthen construction specialist, led students to independently deduce advantages and limitations of various materials based on material properties, manufacturing processes, and lifecycle considerations. Each group received the basic materials needed for brick production (earth, straw, water), the equipment (mold for shaping, trowel, cauldron) and the recipe to follow. Facilitators demonstrated raw earth brick and *massone* forming in stages, allowing student observation before attempting each step independently. This scaffolded instruction supported skill development while revealing individual interpretation variations in executing teorically identical procedures. Following fabrication completion, the group reconvened for collective evaluation. Raw earth bricks and *massoni* exhibiting various quality outcomes (excellent cohesion and form retention, moderate performance,

significant defects) were analyzed systematically. Students identified probable causes of differential results. This analytical process transformed apparent "failures" into learning opportunities, demonstrating that earthen construction requires attentiveness to material behavior, environmental conditions, and procedural precision. In both cases the land was supplied from a land historically used for the construction of raw earth masonry located in the Municipality of San Martino sulla Marrucina (Chieti) which is approximately 35 km from the Municipality of Pescara, thus enhancing the local building culture. Both workshops employed systematic observation documenting: participant demographics; verbal interactions (questions posed, discussions initiated); technical outcomes (successfully formed raw earth brick or *massoni*, quality assessment); and post-workshop feedback (expressed interest, knowledge retention indicators).

3 Results and Discussion

In the "workshop for all," approximately n°110 visitors stopped by the stand to observe the informational materials and the ongoing activities involving the production of raw earth bricks and *massoni*. Of these, only 23 participants chose to actively make a raw earth brick or a *massone*, dedicating about 30 min to the activity. Participants showed a distinct age distribution: ages 5–10: 5 (21.7%); ages 11–18: 5 (21.7%); ages 18–28: 11 (47.8%); over 65: 2 (8.7%). The 28–65 age group showed a complete absence from hands-on participation: they often accompanied and encouraged their children or grandchildren to take part, while remaining observers themselves. Interviews with visitors and observational analysis revealed two contrasting interpretations of the workshop activity. Children up to 11 years old and the adults accompanying them perceived the manufacturing process as a recreational activity. In contrast, participants aged 18 and over recognized the activity as valuable training for skills development. The 18–28 age group actively inquired about material sourcing, regulatory requirements, and professional opportunities in sustainable construction. Interviews with visitors who did not participate in the practical activity identified several deterrents: concerns about getting dirty in the absence of nearby facilities to wash or support the activity; lack of sufficient time to complete the activity (at least 20 min required); and lack of confidence in their ability to successfully make a brick, with the consequent fear of embarrassment.

The university workshop, on the other hand, involved 55 first-year Architecture students, divided into groups of five, and was integrated into the "Materials" course. It presented raw earth construction as a real and contemporary building option rather than a historical curiosity. The facilitated discussion comparing fired bricks and unfired earth blocks proved particularly effective. Participants produced n°11 raw earth bricks and n°3 *massoni*. Despite the guided process and shared base materials, the results showed varying levels of quality. The subsequent analysis phase evolved into a competition for the best brick and generated moments of comparison and mutual support among participants. Common issues included: insufficient initial mixing, which created pockets of straw or unmixed clay lumps that weakened overall cohesion; an excessively plastic mixture causing slumping and poor shape retention; and insufficient manual pressure during forming. Only three bricks were well mixed, with smooth surfaces and adequate compaction. Students therefore identified that identical theoretical inputs produced variable outputs due

to procedural differences in execution. Post-workshop discussions revealed a strong understanding of the principles of earth construction, its environmental advantages, and its technical challenges. The workshop, held in the university courtyard, also created a ripple effect of indirect exposure among passersby (third parties, faculty from other disciplines, and students), generating curiosity and raising awareness on the topic. Both workshops demonstrated that participatory methodologies effectively transmit foundational earthen construction knowledge, though with demographic and contextual variations. Public settings attracted self-selected, intrinsically motivated participants, with limited demographic diversity. Academic integration ensured broader exposure, developing interest through direct experience. All active participants successfully completed fabrication, demonstrating that basic technical procedures can be transmitted in a time between 30 and 60 min. However, the quality of fabrication requires extended practice, confirming that workshop experiences provide entry-level exposure rather than comprehensive mastery. Post-workshop discussions revealed strong comprehension of earthen construction principles, environmental advantages, and technical challenges. Direct contact with the materials highlighted their technical complexity, the skills required, and their current relevance, helping to dismantle preconceptions that rammed earth constructions are obsolete and short-lived. While a single-session workshop "for everyone" is useful to raise awareness in the community, in the case of workshops with university students it doesn't provide sufficient training for a professional use. For them, multi-session progressive training programs would better. Demographic analysis reveals that age significantly influences engagement patterns, with young adults (18–28 years) demonstrating highest participation quality and receptivity. The notable absence of adults from 28 to 65 years, from hands-on participation suggests that cultural norms and contextual factors mediate workshop accessibility, requiring targeted strategies to engage this demographic group, which can have a high impact in terms of potential applicability of



Fig. 2. Phases of raw earth bricks production during the participatory workshops

the use of raw earth. Future editions should include shorter 10–15 min activities, pre-organized washing/support facilities, and low-threshold introductory tasks that reduce performance anxiety. Participants gained tangible understanding that sustainable construction alternatives exist and proven viable across centuries, challenging assumptions that environmental performance requires technological complexity or economic effort. While the workshops have not yet been systematically tracked in terms of direct transfer to completed building sites or formal policy measures, they should be read within the broader regional process of earthen heritage recognition (Fig. 2).

4 Conclusions

This research demonstrates that participatory workshops constitute effective instruments for reintroducing and innovating traditional earthen building knowledge, while advancing broader sustainability objectives including circular economy principles, local supply chain resilience, and community identity regeneration. Given the wide geographical diffusion of earthen architectural heritage, the workshop format presented here can be replicated in other regions, adapting materials, techniques, and communication strategies to the specific local building culture. Scaling earthen construction knowledge dissemination requires development of trainer programs, and open-access educational resources enabling broader geographic reach. Integration within university study path represents particularly strategic opportunity, ensuring that future construction professionals possess foundational knowledge of earthen techniques.

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Synergies for Circularity Networks: Building Open Relationships for Boosting Remanufacturing Loops for High-Value Building Components

Cinzia Maria Luisa Talamo[1], Nazly Atta[1], Giancarlo Paganin[2], and Michele Laurante[1](✉)

[1] Department of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, Milan, Italy
michele.laurante@polimi.it

[2] Department of Architecture and Urban Studies (DAsTU), Politecnico di Milano, Milan, Italy

Abstract. Extending the service life of products and components is key to achieve resource efficiency, waste minimisation, and sustainable consumption. Among the various circular economy strategies, remanufacturing stands out as a high-value recovery approach that enables product life extension and multiple use cycles. Despite that, differently from other industrial fields, in the construction sector the practice of remanufacturing is still underdeveloped. A continuous and consistent reverse flow of building components from renovation sites to remanufacturers is not yet practicable due to some barriers such as low quantities of returned products, difficulties in product traceability and synergistic partnerships among stakeholders. To address these issues, the paper firstly proposes and discusses some innovative circular organisational models characterised by the central role of the Original Equipment Manufacturer (OEM) that, according to different logistic schemes, activates open and collaborative partnerships with multiple end-users to improve the opportunities for the collection of recovered products. Secondly, the paper applies one of the proposed organisational models to the case of an Italian raised flooring manufacturer, intending to verify the suitability of the model to boost synergistic partnerships by engaging multiple end-users involved in office site renovations and to enlarge the source of materials for remanufacturing loops.

Keywords: Remanufacturing · Circularity Networks · Product life extension · Circular Economy · Organisational Models

1 Introduction

Product life extension is receiving increasing attention in policy agendas as a strategic measure to reduce environmental impacts, limit material dependency, and boost economic competitiveness in businesses [1].

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Among the circular economy strategies (reuse, recondition, repurpose and recycling) proposed by international standards [2, 3] and European regulations [4, 5], remanufacturing emerges as a high-value recovery approach able to extend the useful service life of products and components [6].

Remanufacturing is a "value-retention process" [6] that restores used parts, or cores, to "like-new" condition, with a warranty equivalent to an original new product [3]. Remanufacturing enables product life extension and multiple use cycles by minimising material inputs and energy demands, and it reduces acquisition and production costs, possibly allowing products to be marketed at lower prices [7]. Traditionally, remanufacturing practices have been successfully implemented in heavy industrial sectors – e.g., automotive, aerospace, and electronics – characterised by capital-intensive products with long service lives and predictable return flows [8]. In these sectors, manufacturers have progressively optimised supply chains to standardise remanufacturing and increase core recovery volumes. On the contrary, for sectors characterised by irregular return flows and fragmented supply chains, the diffusion of remanufacturing chains still remains highly variable [9].

The construction sector, recognised as one of the most environmentally impactful sectors [4], demonstrates significant delays in overcoming linear model of production and consumption [10] and, in particular, in developing systemic remanufacturing strategies. In 2020, the total amount of construction and demolition waste CDW (excluding soils and dredges) generated in the EU-27 stood at 333 million tonnes, making it the largest waste stream in the EU by weight [10]. Despite various possibilities of recovery, currently downcycling and low-grade operations (e.g., backfilling, energy recovery) still remain the most implemented ones [11]. In this scenario, the amount of building products that at the end of their service life are reintegrated into new construction through reuse or remanufacturing practices remains substantially low [12].

One of the barriers to reuse and remanufacturing can be recognised in the organisational structure of construction supply chains. Building product manufacturers usually do not manage the entire life cycle of their products [13]. Once products are sold and installed, manufacturers are rarely involved in their subsequent use, maintenance, or end-of-life management. Product ownership changes over time, information about performance degradation is seldom collected, and reverse logistics are not systematically organised. As a result, high-value building components such as floorings, ceilings, partitions, etc. – commonly used in tertiary buildings – are frequently directed to landfill and/or downcycling despite retaining material and a significant economic value.

Several scholars argue that to overcome these barriers, the development of open and collaborative organisational models and the enlargement of the geographical basin for the collection of recovered products can be valuable strategies [13, 14].

Starting from this premise, the paper reports the results of a research that investigates new synergistic models aiming to boost remanufacturing loops for recovering high-value building components.

The research proposes three organisational models of increasing complexity, ranging from traditional closed-loop configuration to integrated collaborative networks. To develop the models, a range of stakeholders – including architects, general contractors, manufacturer and tenants – operating in tertiary renewal projects were interviewed

through focus groups and roundtable discussions. These sessions were aimed at developing and refining the organisational models, with specific attention to stakeholder responsibilities, recovery streams, financial flows and coordination processes.

For validation purposes, one of the proposed models was applied to the case of an Italian raised flooring manufacturer, intending to verify the suitability of the model to boost synergistic partnerships by engaging multiple end-users involved in office site renovations, and to enlarge the source of materials for remanufacturing loops.

Overall, the paper aims to contribute to the emerging discussion on circular supply chains in the built environment by demonstrating how collaborative organisational models can support the scaling of remanufacturing practices for high-value building components.

2 Consolidated Remanufacturing Model for the Tertiary Sector

Tertiary sector seems to be particularly responsive to the implementation of remanufacturing practices. Tertiary buildings exhibit a higher rate of material turnover across a building life cycle [15]. These spaces undergo frequent changes within their layout due to, for example, aesthetic updates, corporate rebranding, or changes in tenancy. In these cases, the very short use phase (every 8–10 years) typically leads to the disposal of perfectly functional systems – e.g., raised access floors, suspended ceilings, demountable partitions – that are still in excellent condition while still retaining a significant residual performance [15]. Moreover, these systems often present specific characteristics – e.g., modularity, dry assembly, standardisation – that closely align with those supporting remanufacturing in other industrial sectors [16].

Evidence from stakeholder consultations and the analysis of existing practices reveals some forms of closed-loop relationships between the end user and the Original Equipment Manufacturer (OEM). This relationship can be described according to a "one-to-one" remanufacturing model (See Fig. 1a).

The "one-to-one" model reflects the traditional remanufacturing relationship, in which product ownership and responsibility remain within a mutual exchange between the OEM and the client. According to this model, the OEM maintains direct interaction with the building owner, and the recovered products are reused within the same spatial context in which they are located. The model is particularly suitable in the case of continuous ownership, such as in corporate headquarters or long-term leased assets. Agreements such as renting, product-as-service or leasing may stabilise relationships between OEM and client.

Despite its feasibility, the success of the "one-to-one" model largely depends on two conditions. On one side, the amount of recovered products that can justify the interest of the OEM in activating remanufacturing practice, and, on the other, the willingness of the client to accept remanufactured products. However, the one-to-one remains confined to the relationship between the OEM and the client, and, at present, it does not have the capacity to activate product flows, quantitatively significant and consequently to boost proper and scalable business strategies.

3 New Collaborative Remanufacturing Models for the Tertiary Sector

The limitations associated with the "one-to-one" model highlight the need to explore innovative models for supporting a consistent and reverse product flow from building sites to the OEM. In response to this need, two organisational models are proposed to strengthen remanufacturing loops for high-value building components in the tertiary sector, namely:

1. **Many-to-One Model (Synergistic Aggregation)**: In this model, multiple sites return limited volumes of products, which are aggregated and remanufactured by the OEM for redistribution to a single large project (Fig. 1b).
2. **One-to-Many Model (Synergistic Distribution)**: Within this model, a single site provides a sufficiently large volume of recoverable products, which, after remanufacturing, are redistributed across multiple recipient projects for reuse (Fig. 1c).

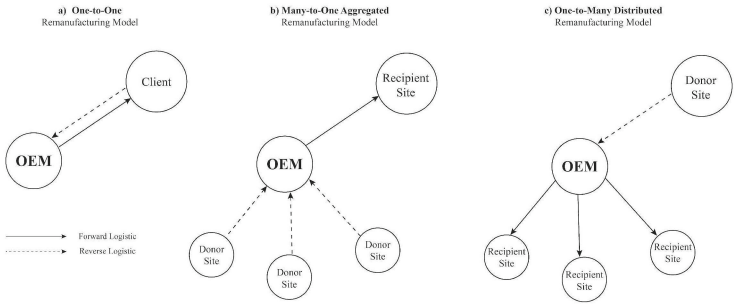


Fig. 1 One-to one (a), Many-to-one (b), One-to-Many (c)

These two models (Fig. 1b and c) derive from the "one-to-one" by progressively expanding the network of actors involved in product recovery and by introducing synergistic mechanisms capable of connecting otherwise independent renovation projects. It is important to notice that the concept of synergy characterising these models does not just refer to the simple collaboration among actors, but relies on the strategic balance of material volumes, incentives to remanufacturing, and interaction across temporally disconnected renovation projects.

3.1 Many-to-One Model: Synergistic Aggregation Configuration

The "many-to-one" model faces the issue of supply-side fragmentation by increasing the volume of recovered products and connecting different project sites.

In this model, multiple sites (donors) return limited quantities of recoverable components, which are aggregated by the OEM for remanufacturing and distributed to a single large recipient project for reuse. Within this structure, the OEM performs a buffering function, both spatially and temporally, by collecting and storing selected heterogeneous

products (both its products and those from other manufacturers) for remanufacturing. Compared to the "one-to-one" model, the OEM assumes more complex tasks, as it has to create and manage relationships with the donors, assess the characteristics and quality of the recoverable products, face the variability across product composition and coordinate reverse logistics among multiple actors.

The viability of this model largely depends on the capability of the OEM to involve many donors and create appropriate logistic chains, and at the same time on the presence of a sufficiently large project available for the supply of remanufactured products. Furthermore, the huge number of interactions between OEM and donor/recipients increases the challenges related to product traceability, characterisation, and assurance of residual performance. Components from different sites may vary in condition, making quality control more difficult, hence requiring careful inspection and assessment before reuse.

3.2 One-to-Many Model: Synergistic Distribution Configuration

Within the one-to-many model, a single donor site provides a large volume of recoverable components, which can be remanufactured and subsequently redistributed across multiple recipient projects. In this sense, the aggregation logic introduced in the Many-to-One model is reversed: a large and concentrated source provides products for reuse/remanufacturing and for small and scattered sites across the territory.

This model represents a strong potential for tertiary renovation projects, where large refurbishments periodically generate substantial recoverable volumes of high-value building components. By redistributing recovered material across multiple sites, the OEM reduce dependency on a single large recipient and diversifies the demand-related risk. Moreover, over time, if the OEM is able to consolidate the relationships and promote exchanges, recipient projects may become donor sites in future renovation cycles, progressively generating an interconnected network of material flows rather than isolated circular loops.

4 Application of One-to-Many Model to a Case Study

The One-to-Many model has been tested on the Nesite company, a leading OEM of raised flooring systems located in Italy.

Nesite supplies raised access flooring panels consisting of calcium sulphate or chipboard cores with an upper layer for resilient or stone finishing, and a lower aluminium layer for backing support.

As part of its business operations, Nesite provides a remanufacturing service dedicated to collecting and remanufacturing discarded Raised Access Floor (RAF) panels from tertiary building sites. In general, remanufacturing activities are focused on their own brand panels.

The possibility of activation of a One-to-Many Model has been studied on the case of a renovation project (the donor site) on a multi-storey office building in Bergamo (Italy), with an area of approximately 2,000 m^2. The intervention concerns the removal of the existing flooring panels, originally supplied by another manufacturer, to allow the installation of a new under Nesite brand. According to the model (Fig. 2), Nesite could

have implemented a take-back incentive scheme, offering new products at a reduced price on the condition that the existing flooring panels are returned. This solution could have reduced disposal costs for the client while securing a sufficient volume of recoverable materials for the OEM.

To assess the possibility of supply of the returned products, a review of the purchase orders received by Nesite from some Clients has been carried out, highlighting the presence of a specific request of another company, seeking remanufactured RAF for four office spaces, ranging between 250 and 400 m^2. This demonstrates the existing conditions for the application of the model that could have been applied according to the following process: (a) identification, (b) floor recovery, (c) remanufacturing, and (d) redistribution to recipient sites.

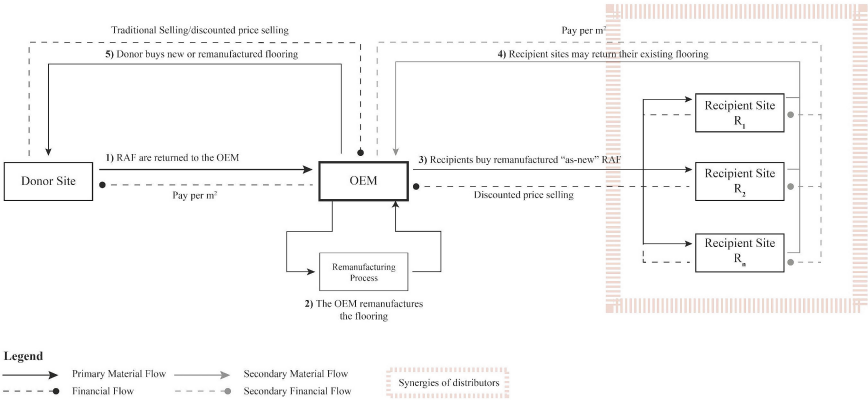


Fig. 2. One-to-many model applied to the Pilot case

To simulate the application of the model, a preliminary technical inspection was conducted to assess the quantity and type of panels suitable for remanufacturing. Results from the preliminary investigation led to the identification of approximately 1800 m^2 of raised flooring panels made of calcium sulphate (34 mm) used for self-laying surfaces, with an aluminium lower surface and four lateral ABS edges glued to the core. Panels located near partitions were considered excluded from the recovery process and sent to recycling. Moreover, because the panels were not originally sourced from Nesite, technical data sheets and the original purchase order were requested by the clients to allow tracing product specifications, identify technical characteristics and analyse the original mechanical performance. Once the material origin and conditions were established, the panels were considered able to be collected and sent to the OEM for remanufacturing. Within this scenario, the absence of any upper surface has been recognised as the best condition for customisation that can be requested by the recipient company. Static performance tests are necessary to ensure the compliance of the regenerated product with "as new" technical performance. In addition, a new identification code should be applied to guarantee traceability throughout the subsequent use cycle.

Overall, the model could enable the reintroduction of a used product into the market for a new cycle of use, hence leading to multiple benefits for the three actors involved.

The receiving client can obtain a regenerated product with high technical performance at a competitive purchase price. The manufacturer can benefit from marketing a flooring product without incurring the high costs of material procurement. Finally, the donor client can gain advantages by receiving a new product while also avoiding significant disposal costs associated with dismantled materials.

5 Discussion and Conclusion

The pilot application with Nesite provides initial evidence of the operational feasibility of the one-to-many model. The results indicate that large office renovation projects can serve as strategic sources of components for remanufacturing, offering a consistent inflow of high value products. The pilot also revealed the key role of OEMs in activating open and collaborative networks of end-users – sources of recovered products' sources – and in coordinating reverse logistic schemes. Particularly, across all proposed models, the following enabling conditions emerge.

- The ability of the OEM to establish multiple partnerships with donor and recipient sites. The OEM should act as a network activator by increasing the supply of recoverable products;
- New roles ("site agents") are required to support OEMs in identifying potential sources of recoverable products, supporting reverse flow coordination and matching supply and demand;
- Clients are more likely to participate when financial incentives and reputational benefits are present;
- Variability in product conditions requires inspection, testing, and grading protocols to ensure performance reliability.

Overcoming the study's limitations, future research should validate the models across multiple cases and integrate quantitative environmental and economic evaluations.

Concluding, the contribution by outlining innovative circular organizational models and related key implementation requirements – including product traceability, systematic technical verification of products, and OEM's ability to coordinate reverse logistics across multiple sites – contributes to promote circular material loops in the construction sector.

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"Closing the Loop in Demolition: Integrating Cascading Audits, Robotics, and Real-Time Digital Monitoring"

I. Díez-Ortiz[1(✉)], D. Salle[1], I. Merino[1], J. A. Ferriz-Papi[2], and O. Fasanmi[2]

[1] Tecnalia Research and Innovation, Derio, Spain
ines.diez@tecnalia.com
[2] University of Salford, Salford, UK

Abstract. This presentation presents an integrated approach to pre-demolition auditing aimed at enabling accurate classification of materials, including their quantities and location within the building, to maximize opportunities for reuse before considering recycling. The methodology is based on a cascading questionnaire that guides decision-making across four possible scenarios, consistently prioritizing reuse as the preferred pathway for each element or material. When mixed material streams are unavoidable, the approach incorporates robotic separation technologies capable of sorting the stream into single-material fractions, significantly improving the quality and efficiency of resource recovery. These processes are supported by the Connected Lab, a digital tool developed within the project that enables real-time acquisition of weight data for each material flow and provides remote visualization of the separation process. This eliminates the need for manual sorting or subsequent component testing, streamlining operations while enhancing accuracy and traceability. Overall, the proposed system strengthens circularity in demolition practices by combining structured auditing, automated separation, and digital monitoring to support informed decision-making and promote higher-value material recirculation.

Keywords: pre-demolition audit · material reuse · robotic separation · circular construction · digital monitoring · resource recovery

1 Introduction

Construction and demolition waste (CDW) represents one of the largest waste streams worldwide and poses significant environmental and resource management challenges. In the European Union, CDW accounts for approximately 25–30% of total waste generation, making it a key target for circular economy policies (La Rosa et al., 2018) [1]. Despite this, current CDW management practices still rely largely on conventional demolition processes that generate heterogeneous and contaminated waste streams. As a result, the recovery of high-value materials remains limited, and many materials are downcycled or disposed of instead of being reused (Duan et al., 2019) [2].

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To address this issue, the European Union has established ambitious circular economy targets aimed at increasing material recovery and moving towards near-zero CDW generation by 2050. Achieving these objectives requires improved methods for identifying reusable materials before demolition begins, preventing valuable components from entering mixed waste streams (Huang et al., 2018; Adams et al., 2017) [3, 4].

Pre-demolition audits have therefore become an essential tool for enabling more circular demolition practices. These audits aim to identify building materials, estimate their quantities, determine their location within the building and assess their potential for reuse (European Commission, 2024) [5]. However, traditional auditing practices remain fragmented, often involving multiple stakeholders and extensive manual data collection. This reduces efficiency and limits the identification of reusable materials before demolition takes place. Recent research has explored the use of digital technologies to improve this process through automated inventories and data-driven decision-making. One promising approach involves the digitization of legacy building documentation. Artificial intelligence can convert paper-based drawings into CAD models, improving the availability and accuracy of building information (Omer et al., 2024) [6]. These models can then be transformed into three-dimensional representations, while augmented reality (AR) tools allow on-site adjustments to reflect the actual condition of the building. This workflow makes it possible to create more reliable digital inventories that capture material types, quantities and spatial locations, supporting improved demolition planning and waste management (Chi et al.) [7].

At the same time, significant progress has been made in automated waste sorting technologies. Robotic sorting systems equipped with multisensory perception pipelines, including hyperspectral near-infrared (NIR), RGB and depth sensors, can analyze waste streams in real time and classify materials using artificial intelligence algorithms (Pires et al., 2021) [8]. By isolating contaminants such as gypsum, glass or wood, robotic systems can significantly improve the purity of recycled aggregates and increase their suitability for reuse in construction (Ghavami et al., 2020; Huang et al., 2020) [9, 10].

Despite these advances, digital auditing and robotic sorting technologies are typically implemented independently. Digital tools mainly support early demolition planning stages (Omer et al., 2024; Cheng et al., 2022) [6, 11], while robotic sorting systems are generally used later in waste treatment facilities (Pires et al., 2021; Ghavami et al., 2020) [8, 9]. As a result, demolition waste management workflows remain fragmented and lack an integrated framework that links auditing, automated separation and real-time monitoring (Huang et al., 2018; Adams et al., 2017) [4, 10].

2 Methodology

To address this gap, this paper proposes an integrated framework combining digital auditing, robotic sorting and real-time monitoring. The auditing process begins with a digital questionnaire based on the *Pre-Demolition Audits 4.0* workflow. This questionnaire evaluates each building element and categorizes it into reuse, repair, recycling or disposal pathways (Adams et al., 2017; Cheng et al., 2022) [4, 11]. The cascading logic prioritizes reuse over recycling by first evaluating whether a building element can be directly reused in its current condition or with minimal repair interventions. Only when

reuse is not technically, economically or functionally feasible does the evaluation proceed to subsequent cascading questions related to recycling or disposal options. This sequential decision-making approach ensures that higher-value recovery strategies are always considered before lower-value recovery pathways. Legacy building drawings are digitized using AI to generate CAD and BIM-compatible 3D models, which are verified through AR-assisted inspections to produce a digital inventory of materials and associated Eural waste codes (Lu et al., 2005; Gimenez et al., 2016; Cheng et al., 2022; Omer et al., 2024) [6, 11, 14, 15].

Mixed demolition waste streams are subsequently processed using an automated robotic sorting unit equipped with hyperspectral NIR, RGB and depth sensors. A one-dimensional convolutional neural network (1D-CNN) identifies materials such as gypsum, concrete, wood and glass in real time, enabling a pick-and-throw strategy that separates waste into dedicated containers. Previous studies have shown that similar AI-based systems can achieve classification accuracies above 85% while significantly improving the purity of recovered aggregates (Pires et al., 2021; Zhao et al., 2022) [8, 13]. In the current pilot, the reported classification accuracy values were primarily obtained under laboratory-controlled conditions using representative material samples. However, the robotic unit was also tested using real mixed samples directly collected from a construction and demolition waste treatment plant, where the system also demonstrated promising identification and separation performance under more realistic operational conditions. The processing speed of the robotic sorting unit can be adjusted depending on the operational requirements and conveyor belt speed. This flexibility allows the system to adapt to different waste flow conditions and material compositions while maintaining stable classification performance.

Material flows are monitored through a digital platform referred to as the Connected Lab. Industrial scales installed at both the inlet and outlet of the robotic system record the mass of each material fraction and transmit the data via OPC-UA to a web-based dashboard. This dashboard visualizes material flows, key performance indicators and mass balances in real time. In addition, integrated IP cameras provide visual verification of the process, while stored datasets allow post-process analysis and performance evaluation (Zhao et al., 2022; Cheng et al., 2022) [11, 13]. Special attention must be given to environmental conditions during operation, particularly regarding dust generation and fine particles commonly present in demolition waste streams. Since the robotic unit relies on optical sensing technologies such as hyperspectral NIR and RGB cameras, excessive dust accumulation may affect sensor performance and material recognition accuracy. For this reason, protective measures and controlled operating conditions are currently recommended to preserve sensor reliability.

Finally, the data generated during the auditing, sorting and monitoring stages feed into a decision-support module that prioritizes reuse over recycling whenever feasible. By considering factors such as structural safety, economic feasibility and logistical constraints, the system identifies the most appropriate recovery strategy for each material stream and supports circular demolition practices (Duan et al., 2019; Ghisellini et al., 2016) [2, 12].

3 Results

Although several technological advances have been proposed to improve construction and demolition waste (CDW) management, several operational challenges still affect the efficiency of current demolition workflows. These challenges arise from the fragmented nature of the demolition process, where material auditing, waste sorting and monitoring are typically treated as separate stages with limited data exchange between them. Consequently, valuable information generated during pre-demolition audits is rarely connected to downstream waste processing activities, reducing the overall efficiency of resource recovery strategies.

In conventional demolition practices, pre-demolition audits often rely on manual inspections, heterogeneous documentation formats and the subjective interpretation of auditors. This leads to inconsistencies in the identification of reusable components and limits the reliability of material inventories generated during the planning stage. At the same time, waste sorting processes carried out in treatment facilities are frequently constrained by the quality of incoming mixed waste streams, which complicates the separation of materials and reduces the purity of recovered aggregates.

In addition to these technical limitations, many existing systems lack adequate mechanisms for monitoring and tracing material flows throughout the demolition and recycling process. Data regarding material quantities, sorting performance and recovery rates are often collected manually or analyzed retrospectively, which restricts the ability to optimize the process in real time. As a result, the absence of an integrated workflow linking digital auditing, automated sorting and monitoring technologies remains a major barrier to the implementation of circular demolition strategies.

To better illustrate these limitations and the improvements introduced by the proposed framework, Table 1 summarizes the main operational challenges encountered in current CDW management practices and compares them with the solutions implemented in this study. The table highlights how the integration of digital auditing tools, AI-based modelling, robotic sorting technologies and real-time monitoring systems contributes to addressing these issues and improving the overall efficiency, traceability and circularity of demolition operations.

As shown in Table 1, the proposed framework addresses several structural limitations commonly observed in conventional construction and demolition waste (CDW) management workflows. These limitations typically arise from the fragmented nature of demolition processes, where material identification, waste sorting and monitoring are treated as independent stages rather than as parts of a unified system.

The introduction of the digital cascading questionnaire significantly improves the efficiency and reliability of pre-demolition audits. By structuring the evaluation of building elements and standardizing the decision-making criteria used by auditors, the questionnaire reduces the dependence on manual interpretation and improves the consistency of the collected information. This structured approach not only reduces the time required to complete audits but also enables the early identification of reusable components that would otherwise be lost during conventional demolition operations.

In parallel, the AI-driven digitization of legacy building documentation improves the accuracy and completeness of audit inventories. Converting paper-based drawings into CAD and BIM-compatible models enables the automatic extraction of information such

Table 1. Current challenges in CDW management and improvements achieved by the proposed framework.

Challenge in current CDW management	Proposed solution	Improvement achieved
Fragmented and time-consuming pre-demolition audits due to manual inspections, multiple stakeholders and unstructured documentation	Digital cascading questionnaire based on the *Pre-Demolition Audits 4.0* workflow, enabling structured evaluation of building elements and automated categorization into reuse, repair, recycling or disposal pathways	≈20% reduction in audit duration and ≈50% improvement in decision-making accuracy through standardized evaluation criteria
Incomplete or inconsistent building documentation caused by paper drawings or outdated CAD files	AI-driven digitization of legacy drawings converting raster scans into CAD and BIM-compatible 3D models, complemented by AR-assisted on-site verification	Automated generation of material inventories including material types, quantities and Eural waste codes, reducing transcription errors
Limited identification of reusable components in conventional demolition planning	Digital material inventory integrated with structured decision rules prioritizing reuse before recycling	Improved identification of reusable building elements and better alignment with circular economic objectives
Mixed waste streams reducing recycling quality	AI-based robotic sorting system combining hyperspectral NIR, RGB and depth sensors with machine learning classification	Material classification accuracy up to 96.5% and improved separation of contaminants such as gypsum, wood and glass
Low purity of recycled aggregates due to insufficient sorting precision	Robotic pick-and-throw separation of detected materials into dedicated containers	Sorted fractions reaching 84% purity by weight and 97% by object count
Lack of traceability of material flows in demolition waste processing	Connected Lab digital monitoring platform integrating OPC-UA scales and real-time data visualization	Continuous monitoring of material flows, automated mass balance calculation and elimination of manual weighing procedures
Limited integration of data across demolition planning and waste processing stages	Integrated digital framework linking auditing data, robotic sorting outputs and monitoring dashboards	Improved transparency, traceability and decision-support capabilities for circular demolition practices

as material types, quantities and waste codes. Combined with AR-assisted inspections, the resulting digital twin provides a reliable dataset for demolition planning and resource recovery analysis.

At the waste processing stage, robotic sorting technologies improve material separation compared with conventional manual methods. By combining hyperspectral sensing, RGB imaging and depth perception, the system accurately identifies material classes, removes contaminants and increases the purity and reuse potential of recovered aggregates.

Another key contribution is the Connected Lab monitoring platform, which ensures traceability throughout the demolition workflow. Through industrial weighing systems and real-time data visualization, it enables continuous monitoring of material flows and operational performance, improving transparency while reducing the need for manual measurements and laboratory testing.

Finally, the integration of digital auditing, robotic sorting and real-time monitoring supports data-driven decision-making that prioritizes material reuse whenever feasible. Overall, the results demonstrate improvements in efficiency, data quality, material recovery and process transparency, providing a strong foundation for more circular demolition practices.

4 Conclusion

Construction and demolition waste (CDW) remains one of the largest waste streams worldwide and represents a major challenge for achieving circular economy objectives in the construction sector. Traditional demolition workflows are often fragmented, with pre-demolition audits, waste sorting and monitoring processes typically carried out as separate activities. This lack of integration limits the identification of reusable materials, reduces sorting efficiency and weakens the traceability of recovered resources.

This paper presents an integrated framework that combines digital pre-demolition auditing, automated material separation and real-time monitoring to support more circular demolition practices. The proposed approach integrates several technological components within a single workflow, including a cascading digital questionnaire for structured audits, AI-based digitization of legacy building documentation, robotic sorting of mixed waste streams and the Connected Lab digital monitoring platform.

The results indicate that the digital questionnaire improves audit efficiency by reducing the time required for inspections while increasing the consistency of decision-making. AI-based digitization of legacy drawings enables the creation of BIM-compatible digital models that automatically generate detailed material inventories, reducing transcription errors and improving data consistency.

At the waste processing stage, the robotic sorting system demonstrated high classification accuracy and effective separation of mixed CDW streams. By combining hyperspectral sensing, RGB imaging and depth perception, the system identifies contaminants and separates materials into dedicated fractions, improving the purity of recovered aggregates. In addition, the Connected Lab platform enables continuous tracking of material flows and recovery rates, providing transparent and traceable information on sorting performance.

Despite the promising pilot results, challenges remain when dealing with dust, gypsum residues and highly heterogeneous waste streams, which can affect the accuracy of automated classification systems. Future work will focus on improving sensor robustness and AI-based recognition capabilities. Overall, the proposed framework demonstrates that integrating digital auditing, automated sorting and real-time monitoring can significantly improve the efficiency, transparency and circularity of CDW management, supporting more sustainable demolition practices and higher-value resource recovery.

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Numerical Assessment on the Upgrading from Low-Rise to Medium-Rise of a Known Prefabricated Composite Modular Building System

Konstantina Karagiannidou[1], Themistoklis Nikolaidis[1(✉)], Nikolaos Nikolaidis[1], and Theodoros Iliadis[2]

[1] Department of Civil Engineering, Institute of Metal Structures, Aristotle University of Thessaloniki, Thessaloniki, Greece
thnik@civil.auth.gr

[2] Iliadis Prefabricated Constructions, 15th km Thessaloniki-Perea, 57001 Thessaloniki, Greece

Abstract. The prefabricated composite modular system using lightweight steel frame members connected with double-shell composite walls that play the role of smart façade elements is known and very effective for low-rise buildings. The novelty of this structure is the prefabricated composite twin walled load-bearing walls, which compose a reliable building system based on innovation and sustainable design, giving various advantages to the structural project, reducing costs and safety. In this paper is investigated the structural performance and the respective cost by upgrading this modular prefabricated system from low-rise to medium-rise buildings. Aiming to obtain a clear perspective of the dynamic performance of the upgrading buildings, a known example of a 4-storey building was simulated and estimated using computer software. This analysis includes evaluation of dynamic performance in relation to a similar known reinforced concrete building. Moreover, a similar evaluation in terms of total structural cost was carried out. The verification of the structural performance showed an optimal way to reduce displacements, buckling loads and bending moments for this type of structures. The proposed system can lead to sustainable buildings in terms of total cost and used materials and resources, with advantages to the structural and seismic behaviour, the quality of construction and the speed of erection.

Keywords: Prefabricated Modular Buildings · Composite Steel-Concrete Structures · Façade Elements · Seismic Performance · Sustainable Design

1 Introduction

Over the last thirty years, in many new high-rise buildings worldwide erected by the use steel and composite structural members due to their reliable methods of construction based on prefabrication [1, 2]. Composite of steel and concrete modules can be manufactured in the factory, in many identical copies under a low-cost, high-quality

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and controlled environment [3–5]. This fabrication process and the respective modular erection include optimal techniques for easy transportation [6], integrated and sustainable building systems. In this field, a previously presented and patented modern system [7], based on steel frames infilled with precast load-bearing composite walls have been proved to be particularly effective to erect low-rase buildings. This efficiency is based on one hand on the minimization in cost due to the required steel weight of members and on the other hand on a reliable bearing capacity in serviceability, ultimate and seismic conditions, with easy dismantle and ability to reuse, the most of its components. Moreover, by using prefabricated elements increases the thermal mass of such building types and decreases possibility of overheating, thermal discomfort and cooling energy needs during the warm period of the year [8]. In the presented research [9], an upgrading of this prefabricated system to medium-rise buildings is numerically analyzed and discussed using a typical example of a 4-storey composite building in comparison to a fully concrete one in terms of bearing capacity, cost efficiency and sustainability.

2 Efficiency of Prefabricated Modular Composite Double Shell Wall System

Steel-concrete composite structures are one of the most advanced structural systems in modern engineering [10, 11], as they combine the high strength and ductility of steel with the stiffness and compressive strength of concrete. Their seismic behavior is of particular interest, as the cooperation of the two materials can be exploited to achieve effective seismic energy attenuation, provided that the design is carried out with clear control of the failure mechanisms.

In this study, is used the precast composite of concrete and steel panel (see Fig. 1), performed in the Laboratory of Experimental Strength of Materials and Structures at the Aristotle University of Thessaloniki [12]. This is a structural infilled panel attached to the columns of the steel frame through bolted joints, providing access for easy assembly and service. This system works as a smart control system and can increase the robustness of the steel frame under seismic action [13]. The chosen bolted connections are suitable for easy precast construction, service, and sustainability. The comparison of this type of panels with other load-bearing elements made as sandwich panels with precast concrete shows that the proposed invention offers a better contribution of the envelope to bearing capacity and to dynamic performance of the building.

The increase of this type of construction to higher buildings is a design challenge. First target is the optimal utilization of the bearing capacity offered by the panels to the structural system. Second target is the limitation of the tensile stresses in the concrete shells due to the increased displacements. This research showed that this limitation with elementary only changes in the preconstruction procedure can leads to limited tensile cracks in the concrete for up to 5-storeys buildings.

The combination of precast concrete and structural steel elements in building prefabrication offers structures with enhanced structural and thermal performance. The high interest in mixed construction is motivated by its efficient employment with modular construction techniques enabling faster erection and completion of many different types of buildings compared to conventional constructional methods. The proposed composite



Fig. 1. View of a typical preconstructed module wall in the track (left) and of composite preconstructed building erection (right).

of steel and concrete modules can be easily manufactured in a preconstruction stage of factory-made components under a quality [14] and a low-cost environment, which are transported and assembled on-site using suitable connections to assure structural continuity. The erection and assembly cost on-site could be decrease by the increase of the repeated prefabricated modules. Practically this can happen when the number of floors increases and the prefabrication expands from low-rise to medium-rise buildings. It Is noted that this structural modular system consists of three lateral resisting mechanisms: (i) contribution of the external steel frame; (ii) direct interaction between the steel frame and the compression diagonal strut in the PCSP; (iii) interaction between the steel frame members and the respective upper steel and lower concrete surfaces through friction contact and shear connection by additional shear steel bars and in-situ concrete layer in the lower one [12].

The contribution of the building element to the structural performance of the building leads to lighter steel components of the main steel framework of the building, which in turn decreases the cost of construction, the transportation and assembly on site, as well as the environmental impact through the whole life cycle. The configuration of the proposed element provides structures with increased structural and thermal performance with a minimized wall width. Along with the reduced section of the steel framework's elements the building envelope occupies a lesser percentage of the built area, allowing for more free indoor space for utilization. At the same time, an extra thermal insulation layer embedded between concrete panels, increasing the energy efficiency. Additionally, the concrete shells of the composite walls provide the necessary thermal mass. The high thermal insulation of the building elements in combination with the thermal capacity of the building elements contributes to the minimization of the energy requirements for heating and cooling and therefore leads to the creation of comfortable indoor climatic conditions with the lowest possible energy use becoming to the philosophy of almost zero building energy consumption [15]. Moreover, the used here composite prefabricated models are easily disassembled for fully recycling or reusing.

3 Upgrading Aspects of the Prefabricated Composite Modular System from Low-Rise to Mid-Rise Buildings

A typical workflow of a prefabricated building of such type includes the following steps at the construction site. After a conventional construction of the foundation, anchors are applied in place of the columns to secure the prefabricated composite modules. After this the composite module walls, that were prefabricated from the factory are transferred to the construction site, the columns are secured to anchors through appropriate steel bolts, always in accordance with what has been defined by the design concept.

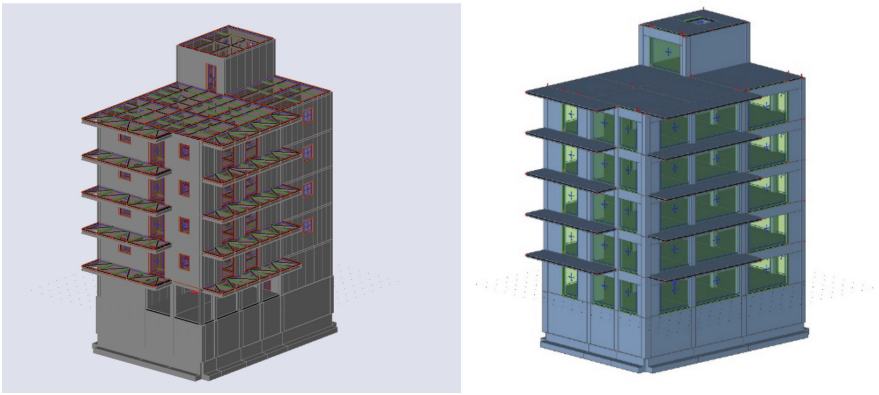


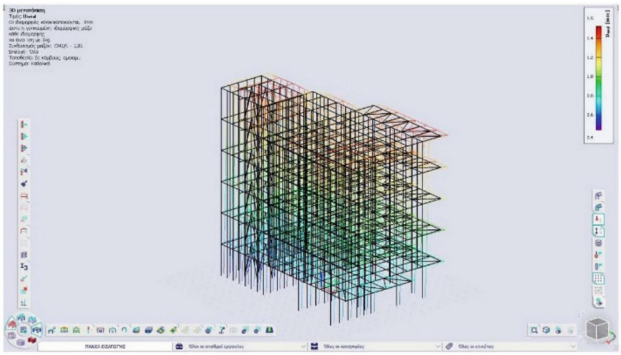
Fig. 2. Simulation models of a composite building (left) and typical concrete building (right).

At this stage and given the general performance of such the system, an investigation is made of the vulnerability to dynamic loads of an upgrading to a representative four-story composite building, in comparison with a corresponding building made of reinforced concrete. The purpose of the work is to evaluate the seismic response and the relative vulnerability of the two structural systems, taking into account modern regulatory requirements and the principles of seismic design. This is followed by the simulation and analysis of the two buildings using the SCIA Engineer software (see Fig. 2), under seismic actions, examining parameters such as the behavior coefficient, soil conditions and seismic zone. Finally, a comparative assessment of the seismic behavior is carried out and critical vulnerability issues are highlighted, regarding the advantages and limitations of this specific composite prefabricated building system compared to conventional reinforced concrete structures.

4 Dynamic Performance and Vulnerability of a Mid-Rise Composite Building with Prefabricated Module Walls

The composite building is a prefabricated structure, which consists of structural members of the previously described system. The load-bearing structure consists of steel frame, on which composite panels and composite slabs are connected. The walls of the load-bearing structure follow the system of prefabricated composite double-shell walls, for

which structural elements an extensive reference has been made previously. These walls are part of the load-bearing system of the building and contribute decisively to the overall stiffness and strength of the structure. The foundation and the basement of the building is constructed entirely of reinforced concrete and consists an independent and sufficiently rigid system for retaining the soil and transferring vertical and horizontal loads to the ground. After a series of numerical tests and checks, the final static model including sizes of structural members emerged, which was used to conduct the analysis.



Eigenmode	Eigenperiod (sec.)	W_{xi}/W_{xtot}	W_{yi}/W_{ytot}	W_{zi}/W_{ztot}	$W_{zi\ R}/W_{ztot\ R}$
1st	0,55	0,0155	**0,8822**	0,0000	0,0036

Fig. 3. First eigenmode (translational in y direction) of the composite building model.

For the seismic analysis, the design spectrum of EN1998 was used, with a design acceleration a = 0.24 g (seismic zone 2), soil category C and behavior factor q = 3. According to the Eurocode 8 classification, the building under consideration falls into category (a), i.e. a moment frame system made of steel or composite elements with connected wall infills made of prefabricated concrete walls.

Initially, the results of the eigenmode analysis for the two respective types of buildings, prefabricated composite and concrete respectively are calculated. More specifically, the values of the eigenfrequencies and the relative eigenmode masses, as well as the main translational and torsional eigenmodes for each building are tabulated. As can be seen, in both cases of buildings the sum of the effective eigenmode masses is ≥90% of the total mass of the building. Furthermore, it is observed that in both analyses the main translational eigenmode in the y direction is the 1st (see Fig. 3), in the x direction the main translational eigenmode is the 2nd and the main torsional eigenmode is the 3rd. The difference arises in the main translational eigenmode in the z direction, where for the composite building it is the 10th, while for the reinforced concrete building it is the 6th. It is worth noting that the percentage of activated mass in the main modes is slightly greater in the case of the reinforced concrete building, while the difference in the main transport mode in the z direction is more noticeable, and this is because the composite building is a lighter structure compared to the reinforced concrete building.

The results of the maximum displacements at each floor for both analyses are presented (see Fig. 4), for the load combinations referred to the main earthquake in x and

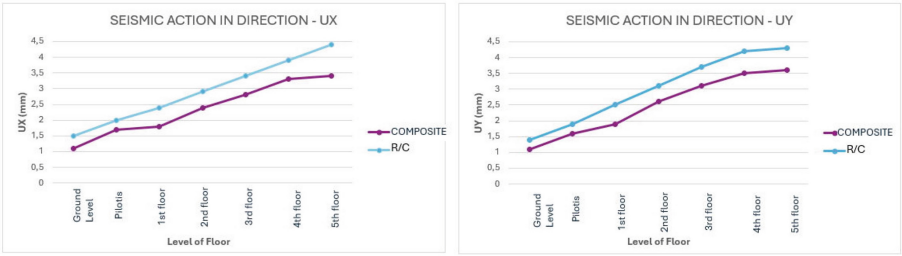


Fig. 4. Seismic displacements in horizontal directions of the building models, composite building results (Cyan), concrete building results (Magenta).

the main earthquake in y, respectively. The reinforced concrete building is a heavier structure compared to the composite building which is a more flexible due to the use of steel frames in the bearing system and that explains the fact that the displacements of the latter are smaller.

In seismic design is very important the degree of sensitiveness of a structure to seismic excitation of a given intensity. This is directly linked to the inherent characteristics of its structural system, such as materials, geometry, typology etc. In this study, the vulnerability of the compared systems investigated through the correlation of structural response quantities, such as displacements, bearing capacity ratios, under the imposed seismic actions for different soil conditions, behaviour factor q and seismic accelerations in respect to the Greek seismic zones. From this comparative examination of the bearing capacity diagrams between the two systems it follows that, for the same seismic assumptions, the reinforced concrete building generally presents higher rates exhaustion of bearing capacity compared to the composite prefabricated building. This behavior is mainly attributed to the differentiated capacity of absorbing and dissipating seismic energy in the two structural systems. In the case of the reinforced concrete building, the limited ductility and the lower energy damping at the structural level leads to increased demands on the individual structural elements, which is reflected in the higher rates of exhaustion (Fig. 5).

On the contrary, in the composite prefabricated building, the collaboration of steel and concrete contributes to more effective absorption of seismic energy and a more uniform distribution of demands, limiting both the tension of the structural members.

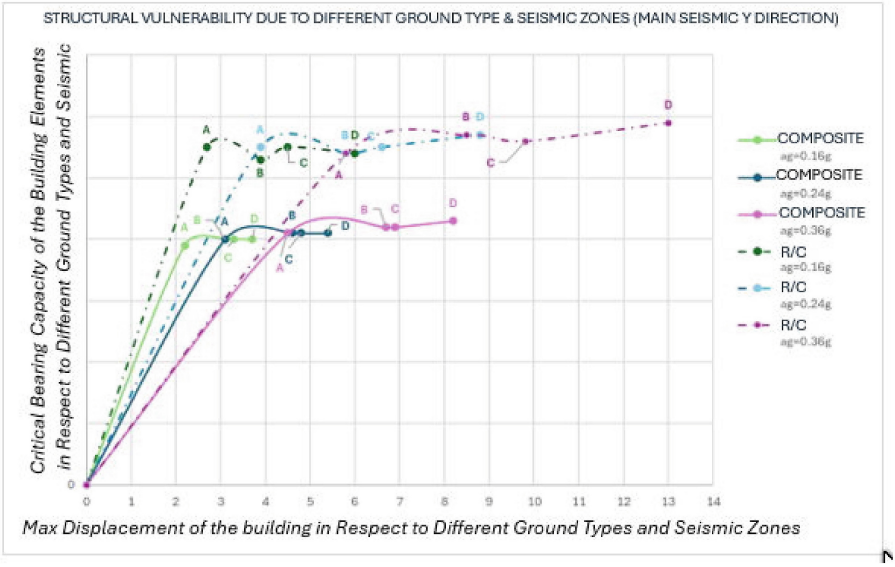


Fig. 5. Bearing capacity ratios of critical structural members for the composite building (continued lines) and concrete building (divided lines) for different response quantities.

5 Conclusions

- The composite prefabricated building exhibits similar stiffness to the corresponding reinforced concrete building, which is usually a design challenge. Moreover, exhibits better torsional behaviour, which is attributed to the targeted and balanced arrangement of the prefabricated double-shell walls.
- Significantly reduced vertical displacements that are observed in the composite medium-rise building, which is attributed to its lower total mass. So, taking into account an equivalent distribution of the composite wall modules to the main directions of the building with considerable stiffness with significant seismic energy absorption with obvious benefits in the safety of the building.
- Under the same seismic assumptions, the prefabricated composite building exhibits lower rates of exhaustion in the bearing capacity of members.
- The configuration of the proposed element provides structures with increased structural and thermal performance with a minimized wall width. Along with the reduced section of the steel framework's elements the building envelope occupies a lesser percentage of the built area, allowing for more free indoor space for utilization.
- The use of this highly effective prefabricated system could be a green and sustainable design choice, especially for medium-rise building cases on high-risk seismic zones.

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Evolution of Circular Economy Themes in the Construction Industry Over Time: A Review Using a Topic Modeling Approach

Hafize Büşra Bostancı[1](✉) and Ali Murat Tanyer[2,3]

[1] Department of Architecture, Hitit University, Çorum, Turkey
busrabostanci@hitit.edu.tr
[2] Department of Architecture, Middle East Technical University, Ankara, Turkey
[3] Center for the Built Environment and Design (MATPUM), Middle East Technical University, Ankara, Turkey

Abstract. The circular economy approach, which is based on the principles of keeping products and materials in the economic system for as long as possible, reducing waste, and regenerating natural systems, has become a strategic model in many fields, especially in the construction industry, over the last decade. Accordingly, interest in the circular economy has been rapidly growing on various themes. This study aims to examine the temporal and thematic evolution of this growth in the circular economy literature at material, building, and city scales. Within this context, scale-specific queries were identified, and articles related to three scales were systematically analyzed to map temporal changes. Journal articles in English in the Scopus database were included. Publication pools were created with queries representing each scale, and text-corpus was prepared by combining the title-abstract-keyword fields in the bibliographic records. Then, Structural Topic Modeling (STM) was applied in the RStudio environment to extract six thematic clusters specific to the scales. The topic trends were interpreted using FREX, and temporal changes between the periods 2015–2019 and post-2020 were compared. The findings indicate that circularity crystallizes differently across scales. While the focus on performance and material substitution strengthens at material and building scales, discussions on adoption barriers, procurement, and indicator-based assessment become more visible at the city scale. This dual-focused analysis aims to create a dynamic discussion, positioning, and research agenda for future work by emphasizing not only current trends and key themes but also less explored research fields.

Keywords: Circular Economy · Construction Industry · Topic Modeling · Digital Technologies · Circular Design

1 Introduction

The worsening negative impacts of climate change have brought sustainability discussions to the forefront of various agendas. Over the last decade, sustainability practices have evolved to the circular economy (CE) paradigm, which aims to keep materials and

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products in the system as long as possible, design out waste, and regenerate natural systems [1, 2]. With the emergence of the CE, the interest in the circular construction industry has gained momentum to tackle the negative impacts of the construction industry, which accounts for 35% of total waste generation [3] and 50% of raw material consumption [4]. So, CE has been addressed from different perspectives in the construction industry, including reclaimed materials, circular transition, assessment tools for circular building design, and stock-and-flow analysis [5]. CE has also been discussed from the perspective of the supply chain and innovative business models [6]. Beyond these, the impact of digital technologies in accelerating the circular construction industry [7] has been part of the circularity agenda, as information flows across life cycle stages is essential for robustly transforming the industry. All these developments could be achieved through a scale-based approach that considers the micro, meso, and macro scales for a circular built environment [8], addressing not only materials and products, but also components, buildings, cities, regions, industries, and systems. Therefore, CE has gained a different reputation as the construction industry differs from other industries due to its own characteristics. As a result, various themes have evolved within this paradigm, with trends and themes reforming over the last decade.

This study employed a quantitative approach combining bibliometric data collection and text mining to examine the thematic structure and temporal evolution of the CE literature in the built environment and construction industry. The literature review was conducted using the Scopus database. The research design was structured around three scales: material scale, building scale, and city scale [9, 10]. Material scale represented the material circularity, including secondary and reclaimed, recycled materials; building scale represented the design for circularity, including DfD, modularity, adaptability, and building lifecycle extension strategies; and city scale represented the urban circularity, including supply chains, governance, urban mining, and metrics. This approach quantitatively reveals thematic divergence across scales and temporal trends by consistently covering a large number of publications set.

2 Method

This study aimed to analyze the evolution of fundamental themes associated with the CE in the construction industry over the years. The analytical framework was structured at the material, building, and city scales to both simplify the literature conceptually and highlight different research clusters along the material-building-city axis. To this end, the themes were analyzed within three scale perspective, and specific queries were defined for each scale. Firstly, the core filter covering CE and the built environment was combined with scale-specific keyword blocks (Fig. 1) to generate a separate publication pool for each scale, which was then labeled as a scale variable in the analysis.

Data collection was performed through the Scopus database in "*Article Title, Abstract, Keywords*". Only peer-reviewed journal articles published in English were included in the study. Conference proceedings, book chapters, editorials, and others, rather than articles, were excluded. The records were exported in a .csv file, including citation information and abstract and keywords, without a time limit.

For text-based analysis, a document-level text corpus was created by combining the title, abstract, and keyword fields of each record in .csv files. Standard preprocessing

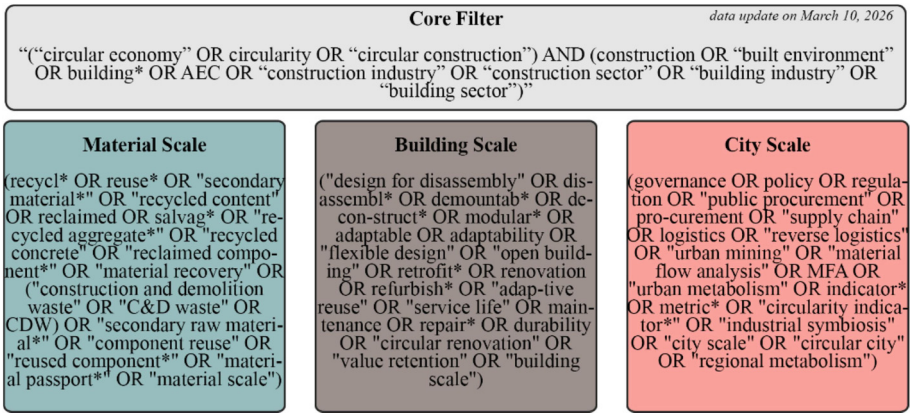


Fig. 1. Boolean queries defined for each scale

steps were applied to the corpus, such as lowercase transcription, removal of punctuation, number, and stopwords, and checking for overly general terms irrelevant to the analysis target. Very low-frequency terms were eliminated according to a specific threshold, simplifying the vocabulary and thus reducing the model's sensitivity to noise.

To reveal the thematic structure and quantitatively track its change over time, analyses were conducted in RStudio using the Structural Topic Model (STM) approach. STM allows modeling the impact of contextual variables on topic prevalence while simultaneously estimating the topic distribution of documents [11, 12]. In this study, the basic contextual variables were defined as year and period classification to compare the temporal changes in CE themes across scales. STM was applied to publication pools created according to the scales, and the number of topics ($K = 6$) was determined considering the theoretical framework and interpretability criteria. The number of topics was kept constant across three scales to maintain inter-scale comparability. A rapid diagnostic assessment ($K = 5–7$) indicated improving model fit with increasing K, while semantic coherence generally decreased. Considering this balance, six topics ($K = 6$) were chosen as an intermediate solution that optimizes both model fit and interpretability. Model outputs were interpreted for each topic using distinctive keywords.

3 Results

Results were evaluated at two levels. First, the trend topics (Table 1) upon FREX terms in each scale were extracted. Second, the annual average topic prevalence was calculated and visualized to track changes over time, and period averages were compared between 2015–2019 and post-2020 (Fig. 2), using 2020 as an analytical breakpoint due to accelerating interest in the CE, rising publication volume in the CE literature, and growing visibility of implementation and measurement tools.

3.1 Trend Topics

Table 1 summarizes the six topics (K = 6) identified for each scale using FREX terms. The six topics obtained at the material scale revealed two dominant lines of research in the CE literature: (i) waste management and (ii) performance-impact assessment of secondary materials. The first line was represented by a cluster highlighting disposal practices such as landfilling and incineration, and particularly plastic-focused streams, including municipal solid waste and construction-demolition waste (CDW) (M1). The second line generated a distinct material-performance focus, involving engineering studies on the mechanical performance of reclaimed aggregates and concrete mixes, including compressive strength, RCA, mortar, and alternative binders, as well as geopolymers (M2). In addition, the environmental impact focus clustered around life cycle assessment (LCA), embodied carbon, and emissions demonstrated that material circularity is considered alongside climate impacts (M4). Functional and multifunctional circular materials constituted a separate research axis in M5. A cluster of topics focusing on batteries and flows, shaped within the context of stock-flow approaches, networks, and machine learning, along a data-driven, systems-analyst-oriented line, stood out. This cluster suggested that the query designed at the material scale also touches upon system-scale analytics (M3). Finally, a cluster of topics in M6 emphasizing cultural heritage, adaptive reuse, stakeholder barriers, and digitalization revealed that adoption, actors, and implementation barriers play a significant role even at the material scale.

At the building scale, the literature pointed to an intertwined understanding of design strategies, assessment, and material innovation. The design-for-circularity approach was strongly differentiated in the context of project and decision-making, particularly with respect to BIM-based tools, adaptability, and design for disassembly (B2). However, demountable structural systems, especially timber load-bearing elements, generated a second set of "design-structural systems" through connection details and reusability (B4). At the building scale, the focus of assessment clustered around LCA, embodied carbon, and emissions (B5) confirmed that environmental performance measurement is a core component at this scale. Yet, the emergence of material-based studies such as recycled aggregates and composite aggregate solutions, such as glass, plastic-reinforced blocks, etc., as a separate topic (B1) and the transformation of material innovations such as binder systems, mortars, fly, ash, geopolymers into a strong cluster (B6) demonstrated that building scale studies largely intersect with material scale in practice. Furthermore, the topic (B3), shaped by themes such as supply chain, policy, social dimension, and cultural heritage and housing, shows that building circularity is discussed not only in the context of technical design but also in governance and implementation.

The topics obtained at the city scale show a distribution closer to the systemic nature of the CE. The waste management axis was highlighted through plastic flows and disposal-recovery processes related to batteries and e-waste (C1). At the city scale, supply chains and actors, along with concepts such as resilience and adaptability, generated a set of issues suggesting that circularity is addressed as a coordination and network management (C2) problem. The climate impacts of material and infrastructure stocks formed an assessment line related to inputs such as concrete-asphalt-cement in the context of GHG and carbon (C3). Adoption barriers and incentive mechanisms stood out as a separate governance focus, especially with procurement practices and awareness

Table 1. Trend topics and sub-topics across scales

Topics	Sub-topics
M1	solid, plastic, municipal, CDW, waste, disposal, demolition, incineration, landfill, plastics
M2	compressive, strength, MPA, RCA, aggregate, flexural, cementitious, geopolymer, powder, mortar
M3	learning, stocks, stock, flows, batteries, flow, China, battery, network, machine
M4	cycle, LCA, life, greenhouse, assessment, warming, timber, embodied, emissions, carbon
M5	insulation, adsorption, wastewater, acoustic, sediments, thermal, wool, biomass, leaching, polyurethane
M6	heritage, adaptive, cultural, barriers, digital, projects, business, stakeholders, interviews, stakeholder
B1	aggregates, recycled, aggregate, concrete, glass, concretes, fine, RCA, plastic, blocks
B2	projects, information, decision, project, adaptability, tool, disassembly, BIM, decision-making, framework
B3	business, supply, chain, housing, heritage, public, policy, innovation, cultural, social
B4	demountable, shear, timber, connections, machine, wood, reusability, beams, learning, structural
B5	cycle, life, LCA, greenhouse, emissions, embodied, gas, stock, assessment, carbon
B6	ash, fly, mortars, conductivity, geopolymer, microstructural, mortar, portland, biochar, binders
C1	plastic, plastics, disposal, solid, treatment, landfill, batteries, recycling, electric, waste
C2	supply, chains, chain, heritage, business, actors, cultural, innovation, resilience, adaptive
C3	wood, emissions, GHG, concrete, asphalt, compressive, thermal, greenhouse, cement, carbon
C4	barriers, adoption, awareness, survey, procurement, factors, design-methodology-approach, drivers, professionals, incentives
C5	design, assessment, cycle, LCA, life, indicators, indicator, architectural, decision, criteria
C6	ecology, spatial, China, stocks, urban, stock, cities, regional, symbiosis, ecological

and survey themes (C4). In parallel, indicator sets, decision criteria, and assessment frameworks constituted a distinct topic field in terms of measuring circularity at the city scale and integrating it into policy and planning (C5). Finally, the topics in C6, which emphasize urban stocks, spatial analysis, regional perspective, and industrial symbiosis or ecology, demonstrated that the "urban metabolism and urban stock" approach and the industrial ecology form a strong thematic stream at the city scale.

3.2 Temporal Changes

The most significant change at the material scale in Fig. 2 is the increasing emphasis on engineering- and performance-oriented studies in the post-2020 period. Specifically, M2 shows a significant increase from 2015–2019 to post-2020; the annual trend graph suggests this increase becomes even more pronounced after 2023. Conversely, M1 and M3 show a decrease in the inter-period comparison; this indicates that the "disposal and waste management" and "stock-flow analytics" axes, which were more dominant in the earlier period, have relatively faded into the background in the post-2020 literature. M4 and M5 follow a more stable trend. Although small increases are seen in the bar graph, annual trends generally show limited fluctuation. M6 has a high share in both periods but has declined somewhat in the post-2020 period; the annual trend indicates a structure that rises around 2016–2018 and then plateaus. The overall picture shows that, at the material scale, the literature after 2020 is increasingly focused on the axis of "secondary material performance and applicability".

The intertemporal divergence at the building scale in Fig. 2 reveals two distinct trends. Between 2020 and 2026, B6 and B1 show significant increases, while B5 and B3 show relatively small decreases. This suggests that the post-2020 literature in the building scale corpus has grown through material substitution and binder and mixture innovation, as much as, or even more than, design and evaluation in some sub-sets. B2 has a visible share in both periods and shows a more limited decrease in the bar graph; the annual trend graph also indicates that this topic has remained relatively stable. B4 shows an annual trend that starts at a very high value in 2015 and rapidly declines, stabilizing at a lower level. Such early-year jumps are often associated with a low number of publications in that year, but can still be interpreted as indicating a sharper focus on "demountable structural systems" in the early years, followed by a greater diversification and dispersion of the literature in subsequent years.

The most prominent feature of the post-2020 period at the city scale is the strengthening of governance and policy tools for adoption. In the bar graph in Fig. 2, C4 shows a very significant increase compared to 2015–2019; the annual trend also supports this result, particularly an increase after 2017 and a higher plateau in the 2020s. In addition, C5 and C3 show limited but consistent increases in the post-2020 period, suggesting that circularity at the city scale is progressing alongside the discussion of "measurability and integration into decision-making processes". On the other hand, C6 and C1 have declined significantly in the post-2020 period; annual trends show that C6, in particular, started high in 2015 and then fell rapidly. C2 remains one of the most dominant clusters with a high share in both periods; however, its relative share has decreased somewhat in the post-2020 period. In general, the city scale in the post-2020 period is shaped as

much, or even more, by adoption barriers, procurement, and governance mechanisms than by "technical management of flows."

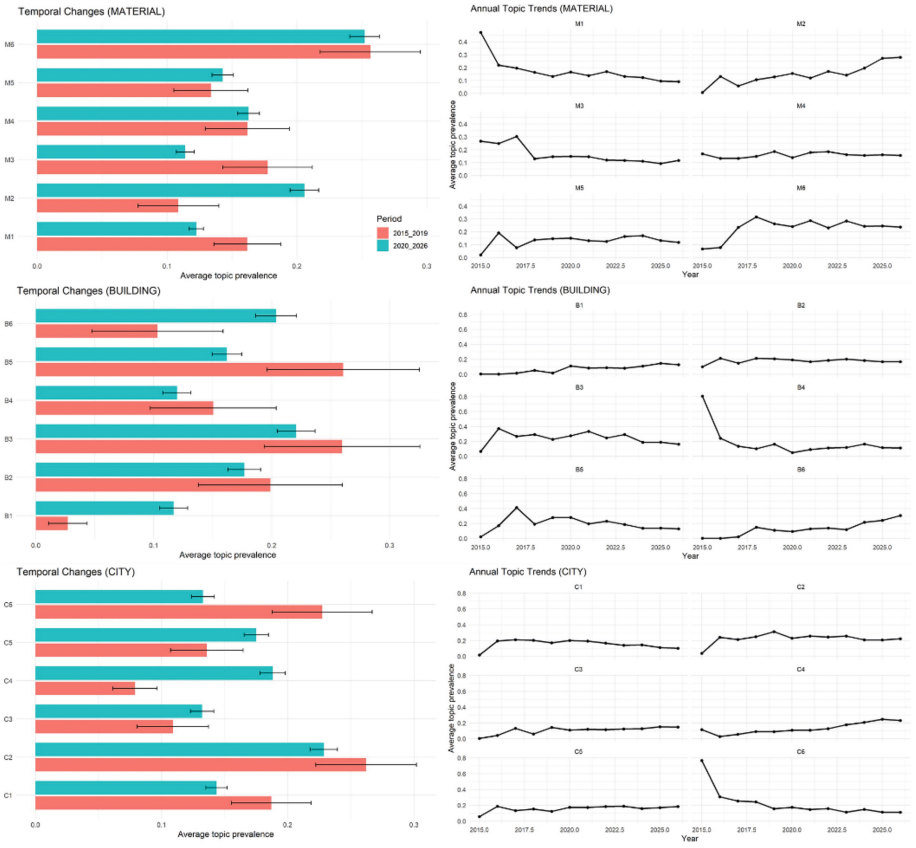


Fig. 2. Temporal comparison and annual changes of topic trends at each scale

4 Conclusion

This study examines CE-construction and built environment literature at the material, building, and city scales, demonstrating how thematic emphasis shifted between the periods 2015–2019 and post-2020. The STM findings indicate that, at each scale, circularity is organized into clusters, including performance and material substitution, environmental impact assessment, reuse through design, and adoption and governance. A temporal comparison reveals that, in the post-2020 period, secondary material performance and binder and mixture innovations have strengthened at the material and building scales, while discussions of adoption barriers, procurement, and indicator-based measurement have become more visible at the city scale.

Because scales are analytical framing, the scale-specific query sets may yield overlapping publication pools. The text field, consisting of title-abstract-keywords, was analyzed in RStudio using STM (K = 6), topics were interpreted using FREX terms, and annual and periodical changes were tracked and indicated. The scope of this study is limited to journal articles indexed in Scopus to ensure interdisciplinary coverage and consistency. Inclusion of additional databases, such as Web of Science, is a future step that could increase the comprehensiveness of the findings. Moreover, the low number of publications in early years may create fluctuations in annual averages, and the analysis relies on bibliographic text fields rather than full text. Nevertheless, the presented scale-based STM framework provides a starting point that systematically allows further refinement of query sets and deeper insights through integrated cross-scale modeling in future studies.

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Learning from Practice: Challenges and Opportunities of Adopting Materials and Building Passports in a Repurposed Building

Ana Rute Costa[1(✉)], Chris Akinrodoye[2], Jeannine de Sousa[3], Thomas Hesslenberg[4], Chidinma Nwaigwe[2], Charlie Vella[4], and Danielle Densley Tingley[5]

[1] Lancaster School of Architecture, Lancaster University, Lancaster LA1 4YW, UK
a.costa@lancaster.ac.uk
[2] Mace Construct, London EC2M 6XB, UK
[3] Norfolk County Council, Norwich, Norfolk NR1 2DH, UK
[4] Elliott Wood Ltd., London SW19 1SD, UK
[5] The University of Sheffield, Sheffield S10 2TN,, UK

Abstract. Through a case study analysis, this paper reflects on the challenges and opportunities of adopting materials passports and building passport for a repurposed building. The case study is a redevelopment of a vacant retail and car park building into a Multi-Use Community Hub (MUCH) in King's Lynn, Norfolk, UK. This building tests the process and practice of adoption materials passports and building passport to support future reuse and maintenance. This approach allows lifecycle data of construction materials, promote transparency and ease responsive reuse. Materials Passports were created for the existing structure, additional structural elements and facade and linked. This paper presents the challenges and opportunities of adopting digital passports in a real-life project, maps the relationship with current and future building regulations and defines three recommendations for future practice: **1) Passporting strategy:** embed requirement at conceptual design stage, bringing whole design team onboard, **2) Passporting scope:** write requirements into tender/specification documentation, with standardised reporting frameworks, **3) Passporting stewardship:** plan where the data will be held, and how it will be passed to and between building owners. We further recommend the development of a national database to centrally hold all passporting information in one secure location.

Keywords: Materials Passports · Building Passport · Digital Products Passports · Construction Products Regulations · Digital Building Logbooks · Practice Insights · Building Information Modelling · Repurpose

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1 Introduction

The global construction industry and built environment are responsible for at least 37% of annual global carbon emissions. The focus on waste reduction, material reuse and extension of buildings' life cycles are the most valuable approaches, with renovation generating 50–75% fewer emissions than new construction [1]. Repurposing existing buildings and making the most of their materials is critical to reduce embodied carbon. In the European Union, the Ecodesign for Sustainable Products Regulation (ESPR) [2] is part of a package of measures that are central to achieve the Circular Economy Action Plan 2020 (CEAP) [3] and foster the transition to a circular, sustainable, competitive economy. The ESPR introduces design requirements to improve durability, reparability, and recyclability across all lifecycle stages. It also establishes the Digital Product Passport (DPP), a key data tool that reports environmental information—mirrored in the Construction Products Regulation (CPR) for the construction sector, which relies on Environmental Product Declarations (EPDs), which are standardised, verified documents detailing a product's environmental impact over its lifecycle. DPPs are a digital identity card for products, components, and materials, which will store relevant information to support products' sustainability, promote their circularity and strengthen legal compliance [4].

However, these regulatory frameworks and tools for construction materials and products are mainly focusing on new products. The focus on embodied carbon is a fundamental step towards meeting the Net Zero targets defined by the UK government. Since 80% of buildings that will exist in 2050 have been already built [5], it is imperative that we make the most of the materials already in existence. The reuse of construction materials is the most energy-efficient circular solution and enables the preservation of material value for longer [6]. At the building scale, the EU proposes the creation of digital building logbooks (DBLs), a comprehensive repository of information that can be used for effective management and decision-making throughout a building's lifecycle [7] it provides information on aspects such as design, construction, quality, and environmental and performance criteria. currently shifting from fragmented, regional guidelines to unified European frameworks. The EU formally tasked the European Committee for Standardization (CEN) with developing two comprehensive standards, a DBL implementation framework and a core data template, which are scheduled for adoption by October 2028. Similarly, in the UK, building owners are entitled to provide a building logbook for new or refurbished buildings. In this case study, we tested the process and practice of Materials Passports (MP) adoption and creation of a Building Passport (BP) for a repurposed and extended building to support future reuse and maintenance.

2 A Case Study Approach: Context and Methodology

This paper is based on a case study qualitative methodology that uses focus group discussions (FGD) and document analysis (DA) research techniques to produce rich and detailed findings. The case study focusing on the redevelopment of a vacant retail and car park building into a Multi-Use Community Hub (MUCH) in King's Lynn, Norfolk, UK. The data collection was led by Ana Rute Costa (AC) and supported by Danielle Densley Tingley (DT), academics which previous research informed the project delivery. We

delivered two FGD with the key stakeholders involved in this project. All the participants on these FGD are co-authors of the paper and have a relevant role in the project delivery: Chris Akinrodoye, Design Manager; David Bentley, Project Manager; Jeannine De Sousa, Client Representative of NCC; Thomas Hesslenberg, Structural Engineer; Chidinma Nwaigwe, Sustainability Manager; Charlie Vella, Sustainability Technician. Document analysis covered: Kings Lynn MUCH Sustainability Strategy, presentations delivered by Elliott Wood with MP Scope, progress delivery, final MP and BP Database and project drawings.

3 Adoption of Materials and Building Passports for a Repurposed Building

3.1 Adoption of Materials Passports and Initial Consideration

As part of a wider aspiration to embed circular economy principles in the project, the client (NCC) defined a sustainability strategy to target BREEAM Excellence, embed robust environmental, social and economic (ESE) framework, achieve LETI 2030 'A' rating and create the first NCC MP and BP database following the policy framework developed [8, 9]. Currently, MPs are not mandatory and the individual case studies are led by individual champions across the Architecture, Engineering and Construction (AEC) industry. Participants agreed that the public sector lacks a unified policy, regulatory framework, or central repository for MP data and the MP adoption relies on isolated initiatives and project-specific resources. In this case study, the MP scope was defined by the client (NCC) and the Engineering team (Elliott Wood). Due to a limited budget and programme constrains, the MP scope comprised the **creation of MP for existing structure and substructure, new structural products and the new façade system.** Elliott Wood has defined the MP templates with the following parameters:

1. **GUID** – Global Unique Identifier produced by Revit to locate that specific element;
2. **PUID** – Project Unique Identifier used to help simplify the location of the element;
3. **Location – Zone** – Only if applicable (e.g., Lobby 1);
4. **Type** – Name of the element (e.g., 150 mm thick RC slab);
5. **Level** – Building level where the element is located (e.g., Level 00);
6. **Description** – Description of the element (e.g., Reinforced Concrete Ground Beam);
7. **Materials** – Material composition (e.g., Reinforced Concrete);
8. **Volume (m^3)** – Total volume of the element;
9. **Area (m^2)** – Total area of the element;
10. **Grade** – Material grade (e.g., RC32/40);
11. **Length (mm)** – Element length;
12. **Width (mm)** – Element width;
13. **Height (mm)** – Element height;
14. **Air Gap (mm)** – Air cavity size if applicable;
15. **Insulation Thickness (mm)** – Thickness of insulation layer;
16. **RICS Building Element** – Classification (e.g., 1.1.1 Standard Foundations);
17. **Manufacturer** – Name of the manufacturer + **Certification Number.**
18. **Warranty Info** – Warranty period (e.g., 10 years);

19. **Design Codes / Standards** – Applicable design codes (e.g., BS 8110);
20. **Test Data** – Test information (e.g., Schmidt Hammer Test – 15 Nm);
21. **Coating** – Surface coating specification (e.g., skid-resistant coating);
22. **Data Source** – Link or reference to the source of the data;
23. **Installation Date** – Date installed (e.g., 01.01.2030);
24. **Lifespan** – Expected service life (e.g., 60 years);
25. **Weight (kg/m or kg/m^2)** – Element weight per unit length or area (e.g., 45 kg/m^2);
26. **Maintenance** – Maintenance requirements (e.g., inspect every 10 years);
27. **H&S** – Health and safety considerations during construction and lifespan;
28. **Condition (if existing/reused)** – Condition notes (e.g., small cracking to face).
29. **Connections** – Connection information if applicable (e.g., steel plate bolted);
30. **Fire Resistance** – Fire rating (e.g., 90 min);
31. **Colour** – Element colour (e.g., grey);
32. **Changes After Install** – Any post-installation modifications (e.g., opening cut in slab);
33. **Proposed EoL Strategy** – End-of-life strategy (e.g., demolished and used as aggregate);
34. **Disassembly Instructions** – Method for removal (e.g., pneumatic breaker);
35. **Salvageable Mass (%)** – Percentage of material recoverable (e.g., 40%);
36. **H&S Considerations** – Safety considerations during demolition process.

A simple data template was developed in Microsoft Excel to record key information relating to the building elements assessed within this study. The template consists of four worksheets: **existing structure, proposed structure, existing façade, and proposed façade**. Each worksheet contains a consistent set of parameters intended to capture essential information about individual building products, including identification, location, material composition, geometric properties, and basic lifecycle attributes.

3.2 Data Collection Process

For the existing structural elements, the MP data collected was informed by site surveys, point cloud data and intrusive surveys (Concrete Testing). This enabled the documentation and characterization of the existing primary and secondary structure to be reused. For the new construction elements, the data was managed by Mace Construction and sourced by subcontractors via a shared template developed by Elliot Wood. This intended to be a simple tool, however, due to 1) lack of familiarity of MP framework, 2) absence of Environmental Product Declarations (EPDs) and 3) subcontractor tendency to overshare all data rather than carefully select the required data, the data collection process resulted in substantial data being discarded and cleansing effort by the design and sustainability teams. Building Information Modelling (BIM) protocols were not adopted for this project and were only employed for clash detection among the design teams. As a result, data had to be extracted manually using Revit's scheduling features, meaning that the MP database relied heavily on spreadsheets and manual inputs.

3.3 Main Challenges of Adopting MP and BP for a Repurposed Building

Despite the guidance provided by the sustainability strategy, the communication and early coordination of MP was one of the main challenges identified by the stakeholders since they were not aware of individual and collective expectations of MP delivery. In this case study, a single MP database was created alongside the project delivery without intermediate deadlines or data handover and therefore the process did not seem linear, straightforward or efficient. Concurrently, the lack of industry maturity in this field caused challenges, the subcontractors had limited understanding of MPs and circularity and perceived MP's creation as an additional administrative burden. Since the construction sector does not have a standardized data infrastructure for MP, the reliance on Excel spreadsheets and manual coordination made MP adoption more challenging. Furthermore, with no clear guidance or nationally agreed approach on long-term storage, ownership, or accessibility of MP/BP data, there is a risk that the data produced could be lost and not used to inform future CE practices.

3.4 Lessons Learned and Recommendations for Future Adoption

Following MP strategy guidance [8], and aligned with this project delivery, the participants believe that MP scope should be defined at the beginning of a project, RIBA Stage 1–2. However, this should then be embedded in subsequent tender documentation, with defined deliverables for subcontractors supported by clear data collection templates. The data collected within the MP and BP can be optimized and integrated into other required documentation, e.g. O&M manuals, Golden thread requirements, Whole-life carbon assessment and BREEAM documentation. The long-term intention is that the MP database can inform circularity initiatives and future regulations, e.g. future deconstruction, material traceability and reuse, carbon taxation compliance, and quantification of a property portfolio. Overall, the stakeholders involved in this case study believe that MP adoption can potentially drive competition among subcontractors, where those ready to provide MP data can gain advantage.

3.5 Building Passport Delivery

The BP was completed based on the template provided by Sheffield University [9]. The BP is composed by the following sections: 1) Building Overview; 2) Building Record; 3) Building Design, 4) Building Energy Performance; 5) Appendix. The MP are nested within the BP created, as recommended by Costa & Hoolahan [8].

At this stage, BP is substantially complete, with only some outstanding test data relating to EPC ratings. All elements were relatively straightforward to populate, as the BP primarily provides an overview for the user, indicating where detailed information can be found. Much of the data it contains is already documented elsewhere, so compiling the BP was largely a collation process. The main challenge lies in ensuring that the information remains up to date as the project evolves, which is a common consideration in any passporting approach. The MP informed BP by supplying detailed material-level data, ensuring that the BP accurately reflects the building's composition and specifications.

3.6 Reflections on passporting's Value and Case Study Limitations

This project helped to recognize the passporting's value and its integration with wider building data requirements. However, there is still a lack of long-term passporting MP data stewardship. Without a clear strategy and regional/national centralized database, data risks being lost, unused, fragmented or unusable over time. All the participants in this study agree that the lack of national leadership on passporting within the UK poses a challenge, and that this would be essential for widespread updating of passporting approaches.

This case study focused on the creation of MP for existing structure and substructure, new structural products and the new façade system, allowing us to test MP for existing and new materials. Recording MP data for existing products is useful to define the conservation state and surveys made. This data can also be used to inform savings on embodied carbon. The MP data for new products can be potentially informed by the coming DPP. The MP database produced represent a small portion of materials used in the building. Capturing wider building layers, particularly those with more frequent replacement rates, e.g. services, could present different opportunities for building maintenance, and shorter-term reuse. This case study demonstrates that while MPs have a strong potential to support CE metrics, their implementation in real-world projects is constrained by current industry practices, fragmented guidance, lack of regulations or institutional support. This project highlights the importance of early planning, digital integrations, and policy leadership. MP are valuable CE tools but require systemic change to deliver full value.

4 Discussion & Recommendations

4.1 Collective Understanding of the Role of Materials Passports and Building Passports for a Repurposed Building

In this case there was a single MP database along all RIBA Stages of work. However, the MP policy paper [8] suggests the creation of 1) Basic MP database for the existing materials at RIBA stage 2, 2) Proposed MP database during the design phase between RIBA Stage 2–4, and 3) Completed MP database once the construction has finished (RIBA Stage 5–6). Unfolding the MP database according to the nature of MP (for existing or new materials) and aligning it with the design and construction phases would facilitate allocation of responsibilities and stakeholders involved in the data collection process. Furthermore, in this case study it was perceived that there was a lack of collective understanding of the role and value of materials passports for a repurposed building. Despite the client leadership and the commitment of the construction and engineering team, there is a need to upskill the wider AEC industry. The MP data can be used to inform diverse circular metrics and other regulation requirements [10], however, these links are not clear or straightforward. Our findings align with those of Jones, Farghaly and Toth [11] who argue that regulatory bodies must harmonise information requirements and data specifications across policy instruments to improve efficiency and reduce compliance costs. Achieving this will require coordinated action from policymakers, financial institutions, and industry leaders to develop a transparent, efficient, and futureproof data ecosystem for the built environment.

4.2 Materials Passports and Building Passports Alignment with Current and Future Regulations

The principle of a MP [12] is similar to a DPP, and it follows the characteristics of a passport for circular economy identified by Capelleveen et al., [13]. The CPR provides harmonised rules for the marketing of construction products in the EU and defines a common technical language to assess the performance of construction products. The revised CPR, launched in January 2026 [14], adds requirements for recyclability, disassembly, durability, repairability, and recycled content for new products. This is a great step for future circularity in the built environment, however, the current CPR and DPP regulations consider products as independent entities. According to MP frameworks published earlier [8, 15, 16] a level approach is recommended where products are nested with wider hierarchy levels/types. As pointed out previously, by centralising DPPs of a building in a single database would facilitate CE metrics and inform future maintenance and disassembly processes. The Digital Building Logbooks (DBLs) are centralized, secure, online repositories that store relevant data about a building throughout its entire lifecycle, are a key enabler of seamless data exchange across the real estate market [11]. Several data sources on buildings already exist at different levels in Europe, and their interoperability is crucial for a proper data population of the future DBLs [17]. Future research is needed to understand the alignment of DPP, CPR and DBLs and potential integrate MP of existing materials/products/elements/systems. Due to increased demand of data transparency in the built environment and proliferation of unaligned reporting standards and regulations, there is an urgent need for a nationally agreed base data structure for passporting to allow interoperability of building and product information between passporting platforms. Furthermore, a central digital database to store and link to all passporting information would ensure that there is one location to source information in the future, reducing the risk of data being lost during building handovers and sales.

Different approaches are needed for passporting for new construction versus existing buildings. For new construction, passporting could be mandated as part of an expansion of 'the golden thread' [18] UK building safety act, where building design and construction information for higher-risk buildings must be held, and kept up to date to ensure building safety throughout its lifecycle. In contrast, existing buildings often lack any information about their design and the materials within them. Material stock modelling approaches can be used to provide rough estimates about potential materials available for salvage. Although pre-redevelopment or demolition audits will capture more detailed and accurate assessments at the individual building level. When carried out, ideally these audits, and additional information, e.g. structural surveys could be held in a centralised platform to detail what is known about the building. These can then be developed into existing MP databases and inform renovation and repurpose design strategies.

4.3 Recommendations and Closing Remarks

This case study highlights the importance of delivering **1) Passporting strategy:** embed requirement at conceptual design stage, bringing whole design team onboard, **2) Passporting scope:** write requirements into tender/specification documentation, with standardised reporting frameworks, **3) Passporting stewardship:** plan where the data will be

held, and how it will be passed to and between building owners. We further recommend the development of a national database to centrally hold all passporting information in one secure location. Meanwhile, initiatives like MUCH project show that AEC industry can rapidly upskill and adopt MP and BP to centralise data collected throughout the design and construction and inform wider CE metrics and building requirements.

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Transforming Decommissioned Wind Turbine Blades into a Scalable Airport Parking Infrastructure System

Ahmed K. Ali(✉)

Texas A&M University, College Station, TX 77845, USA
ahali@tamu.edu

Abstract. The rapid expansion of renewable energy technologies has introduced new environmental challenges associated with end-of-life components of infrastructure. Wind turbine blades (WTBs), typically composed of fiberglass-reinforced composite materials, are difficult to recycle due to their heterogeneous structure, large dimensions, and the technical challenges associated with separating constituent materials. As a result, most decommissioned blades are currently disposed of in landfills. With lifespans ranging from 20 to 35 years, cumulative global WTB waste is projected to reach approximately 43 million tons by 2050, highlighting the need for scalable waste management solutions. This study proposes a design-driven repurposing strategy that transforms decommissioned WTBs into structural shading elements for large parking infrastructures. Blade sections are reused with minimal processing and arranged to enhance airflow and passive cooling in extensive paved environments. A case study application for airport parking facilities integrates repurposed blades with photovoltaic panels and geothermal wells to generate electricity and power site lighting. By converting end-of-life blades into functional infrastructure components, the proposed system extends material lifecycles, mitigates urban heat-island effects, and generates renewable energy. The concept establishes a form of industrial symbiosis between the wind energy sector and airport infrastructure systems, demonstrating a practical pathway for implementing circular economy principles in renewable energy waste management.

Keywords: Wind Turbine Blade · Creative reuse · Infrastructure · Industrial Symbiosis · Circular Economy · Airport Parking

1 Introduction

The global transition toward renewable energy is accelerating amid rising energy demand, population growth, and the urgent need to reduce greenhouse gas emissions. Wind and solar energy have become central components of this transition, enabling countries to diversify their energy portfolios while reducing reliance on fossil fuels. In the United States, renewable sources now account for more than 22% of electricity generation, with wind and solar accounting for a significant share of that output (U.S. Energy Information Administration, n.d.; Navarkar et al., 2020).

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Despite their environmental benefits, renewable energy systems generate significant end-of-life (EoL) waste streams. Wind turbine blades (WTBs) are constructed primarily from fiberglass-reinforced polymer composites designed to withstand extreme environmental conditions. While these materials provide durability and structural strength, they also make recycling difficult due to their layered composition and chemical bonding. As a result, most decommissioned blades are currently disposed of in landfills. Global projections indicate that cumulative WTB waste could reach approximately 43 million tons by 2050 (WindEurope, C., & EuCIA, 2020; Liu & Barlow, 2017). Similarly, solar photovoltaic panels (SPs), which typically have lifespans of around 30 years, are expected to generate 60–78 million tons of waste during the same period (International Renewable Energy Agency, 2016; Vekony, 2021). Current recycling and reuse practices remain limited, leaving large quantities of materials underutilized. Addressing these challenges requires moving beyond purely technical recycling approaches toward design-driven strategies that reimagine waste materials as valuable resources. Within the circular economy framework, repurposing infrastructure components offers opportunities to extend material lifecycles while reducing environmental impacts. This study proposes a scalable infrastructure concept that repurposes decommissioned wind turbine blades as modular shading structures for large parking areas. When integrated with photovoltaic panels and geothermal systems, the design provides shading, passive cooling, and renewable energy generation. By linking renewable energy waste streams with transportation infrastructure, the approach establishes a form of industrial symbiosis that supports sustainable urban development.

1.1 Circular Economy and Renewable Energy Waste

The circular economy (CE) framework promotes strategies that extend product lifecycles and minimize waste generation. While traditional sustainability models emphasized the "reduce, reuse, recycle" hierarchy, recent CE frameworks have expanded this concept into a broader set of strategies often referred to as the 12R framework, including refuse, rethink, redesign, repair, refurbish, remanufacture, repurpose, recycle, and recover (Cramer, 2017). Among these strategies, reuse and repurposing are particularly valuable because they preserve the embodied energy and structural integrity of materials while minimizing additional processing. Several research initiatives have explored potential second-life applications for wind turbine blades. The Re-Wind project has investigated repurposing blades as structural elements for pedestrian bridges, demonstrating the feasibility of using their aerodynamic form and composite strength in civil infrastructure. Similarly, Netherlands-based Superse Studios has incorporated decommissioned blades into urban furniture and playground installations with minimal modification. Other initiatives, such as the ECOBULK project, have explored the reuse of composite materials across construction and manufacturing sectors. While these efforts demonstrate promising design approaches, most remain at demonstration scale and address only a small portion of the projected waste stream. The lack of large-scale applications capable of absorbing significant quantities of decommissioned blades highlights the need for infrastructure-based reuse strategies.

In contrast to wind turbine blades, research on repurposing solar panels remains limited. Most current approaches focus on recycling rather than reuse, often excluding panels that exhibit degradation or physical damage. As renewable energy deployment continues to grow, identifying scalable reuse strategies for both WTBs and SPs will become increasingly important. Infrastructure systems that require large structural elements represent promising opportunities for repurposing these materials. Parking structures provide expansive surfaces that can be shaded to reduce thermal loads while integrating renewable energy generation.

2 Methodology

This research employs a design-based methodology that integrates architectural design exploration with engineering feasibility analysis. The research process consists of four primary stages. First, a literature review was conducted to examine circular economy strategies and existing repurposing initiatives for wind turbine blades and composite materials. This review identified key design opportunities and limitations associated with current reuse practices. Second, a material assessment was performed to evaluate the structural properties, dimensions, and potential reuse configurations of typical decommissioned wind turbine blades. The analysis considered blade geometry, weight, and structural characteristics relevant to infrastructure applications. Third, a conceptual infrastructure system was developed to explore how blade segments could be integrated into modular shading structures. The design prioritized minimal processing to preserve structural integrity and reduce energy consumption associated with material modification. Finally, a case study evaluation was conducted using a large parking facility at George Bush Intercontinental Airport (IAH) in Houston, Texas. The case study examined the spatial requirements, material quantities, and potential renewable energy generation associated with implementing the proposed system in a real-world context. This methodology enables evaluation of the system's scalability, environmental benefits, and feasibility for large infrastructure applications.

3 Results

3.1 Literature Review

Current WTB waste management approaches primarily focus on recycling and landfilling. However, recycling technologies for composites are still in early stages of development and are rarely economically viable on a large scale (WindEurope, C., & EuCIA, 2020). The renewable energy sector is fully committed to producing 100% recyclable turbines by 2040 (Recyclable Blade, n.d.). Through ongoing efforts and innovations, they are actively working towards increasing the recyclability of wind components. However, until recycling technology is available, decommissioned stock will continue being sent to landfills. These challenges highlight the need for alternative strategies that are both environmentally responsible and economically and socially feasible. Repurposing as a CE strategy offers a promising alternative. Unlike recycling, repurposing does

not require breaking material into its raw components, reducing cost and energy consumption. Recent design-based efforts have explored how decommissioned WTBs can be used in infrastructure applications, ranging from playgrounds to pedestrian bridges (Mavrokefalidis, 2021; Superuse Studios, n.d., Web-4). However, most of these projects remain at the single-attempt and demonstration-scale intervention stage.

Large, paved surfaces, such as parking lots and transportation infrastructure, significantly contribute to urban heat island effects. These surfaces absorb and retain solar radiation, raising local temperatures and increasing cooling demand. The city of Houston, Texas, is characterized by a highly car-dependent urban structure. Parking infrastructure occupies a substantial portion of impervious land area, particularly near transportation hubs. The city experiences approximately 90 fully sunny days and 114 partially sunny days per year, exposing vehicles and pavement surfaces to prolonged solar radiation. As one of the largest transportation hubs in the United States, George Bush Intercontinental Airport (IAH) accommodates hundreds of thousands of travelers daily and requires extensive parking infrastructure. Vehicles parked in uncovered lots are vulnerable to heat-related damage, including deterioration of interior materials and reduced functionality of safety systems. These conditions create an opportunity to introduce shading systems that simultaneously reduce surface temperatures, improve user comfort, and generate renewable energy (Fig. 1).



Fig. 1. A typical decommissioned WTB landfill, Source: the web.

3.2 Material Assessment of WTBs

The proposed carport design provides a scalable, feasible, and innovative partial solution to the massive waste problem posed by decommissioned WTBs and SPs. The main issue to consider when searching for a scalable solution is the ability to deliver solutions that meet the region's local needs and are close to the area where the waste is generated. The main factor in ensuring scalability is maintaining a balance between the amount of waste generated in that region and its level of use; additionally, the solution can be repeatable. Its modular nature and dual functionality, providing shade and generating renewable energy, highlight its potential to address specific regional challenges, such as urban

heat islands and energy demands in car-centric cities such as Houston. Additionally, the design can use new solar panels rather than decommissioned ones. Thus, the idea can also contribute to the installation of charging infrastructure for electric vehicles. Carport design demonstrates a design that requires minimal blade cutting, reducing energy use and environmental hazards associated with blade segmentation. This approach aligns with ongoing efforts to optimize processing methods.

The proposed infrastructure system repurposes wind turbine blade sections as structural shading elements installed above parking rows. Blade segments are mounted on steel frames and arranged to create modular carport structures that provide shade while maintaining natural airflow beneath the canopy. The aerodynamic curvature of the blades promotes passive ventilation, reducing heat accumulation within the parking area. The design requires minimal cutting or modification, preserving the structural integrity of the composite materials while minimizing energy consumption during processing. Solar photovoltaic panels are integrated into the upper surfaces of the structure to generate renewable electricity. The panels supply energy for LED lighting, security systems, and auxiliary infrastructure loads. In future implementations, the system could also support electric vehicle charging infrastructure.

3.3 Conceptual Infrastructure System Development

The design was developed for an existing parking lot at George Bush Intercontinental Airport, a surface parking facility covering approximately 83,654 m^2 and accommodating approximately 2,951 vehicles. The proposed system consists of modular units arranged in two rows of parking spaces facing each other. Each module shades approximately 26 vehicles and incorporates blade segments mounted on steel columns. The design requires 681 wind turbine blades, each approximately 37 m in length and weighing around 2.5 tons, and 1,552 photovoltaic panels, each measuring 1×2 m. Repurposing these materials diverts approximately 1,702.5 tons of composite waste from landfills while creating shaded infrastructure for the parking facility.

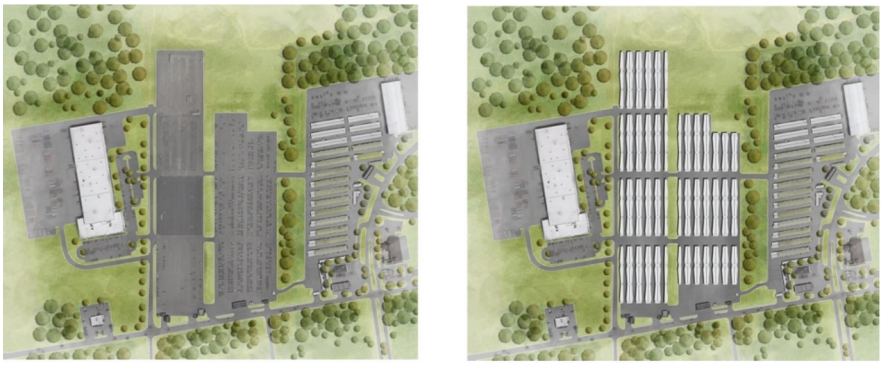


Fig. 2. Before and after rendering for Parking lot 2 on Will Clayton at IAH. Source: Author

3.4 Case Study Evaluation

This innovative carport concept is designed to be implemented in pre-existing or newly built parking lots, benefiting both vehicles and passing pedestrians. The inspiration for this design came from the pattern of decommissioned blades that end up in landfills. The authors developed a design based on the use of whole decommissioned blades. Parking Spot 2, which covers approximately 83,654 m^2 and is located on Will Clayton at IAH, was chosen as a potential application site. The primary material used for the design is steel, with various types of hardware supporting the turbine blades and solar panels. 681 decommissioned blades (37 m long) and 1552 decommissioned solar panels (1 × 2 m) were used to design this open parking lot with a total capacity of 2951 cars (Fig. 2). A two-row module, where vehicles can park facing each other between two axles (column-to-column), can shade 26 cars. A 37-m wind turbine blade weighs approximately 2.5 tons, based on average values reported for medium-length composite blades (Liu & Barlow, 2017; WindEurope, C., & EuCIA, 2020). Accordingly, the design diverts an estimated 1,702.5 tons of composite waste from landfills, which are otherwise difficult and energy-intensive materials to recycle. The integrated photovoltaic panels generate approximately 55.7 kWh per month per panel, providing renewable electricity for site lighting and operational systems. Over five years, the system is projected to produce approximately 5,187,120 kWh of electricity. Based on U.S. Environmental Protection Agency emission factors, this level of electricity generation could offset approximately 1,936.75 tons of carbon dioxide emissions. The WTB supporting structure will integrate geothermal wells to power charging stations. In addition to energy production, the shading structures reduce pavement temperatures and mitigate urban heat-island effects by reducing solar radiation absorption across large, paved surfaces.

4 Discussion

The increasing volume of renewable energy infrastructure reaching the end of its life presents a growing environmental challenge. Repurposing strategies that extend the life-cycle of these materials offer an important complement to recycling technologies. This research demonstrates how decommissioned WTBs can be integrated into urban infrastructure systems with minimal processing. By combining material reuse with renewable energy generation, the proposed design addresses multiple environmental challenges simultaneously. Unlike many existing repurposing initiatives, which remain limited to small-scale demonstrations, the proposed system emphasizes scalability and repeatability. Its modular design allows implementation across large parking facilities, making it suitable for airports, stadiums, logistics centers, and commercial developments. The concept also illustrates how industrial symbiosis can be achieved by linking waste streams from the renewable energy sector with infrastructure needs in the transportation sector. Such partnerships could reduce landfill waste while providing cost-effective construction materials. However, several challenges must be addressed before large-scale implementation becomes feasible. Transportation logistics for large blade segments remain complex, and efficient strategies for blade segmentation and transport will be necessary. Structural performance and long-term durability must also be evaluated through detailed engineering analysis and life-cycle assessment. Despite these challenges, the

concept demonstrates the potential of design-driven repurposing strategies to transform renewable energy waste into valuable infrastructure components (Fig. 3).



Fig. 3. Renders of the proposed carport made from decommissioned WTBs. Source: Author

5 Conclusion

This research presents a scalable infrastructure concept that repurposes decommissioned wind turbine blades and solar panels as modular carport systems for large airport parking facilities. By transforming renewable energy waste into functional infrastructure, the proposed design demonstrates how circular-economy principles can be applied in the built environment. The case study application at George Bush Intercontinental Airport illustrates the environmental and operational benefits of the system, including reduced landfill waste, renewable energy generation, and mitigation of urban heat island effects. The modular design allows adaptation to different parking configurations and blade sizes, supporting scalability across diverse urban contexts. Although the proposed system represents only a partial solution to the growing challenge of renewable energy waste, it provides a practical framework for integrating material reuse with sustainable infrastructure design. Future research will focus on structural optimization, life-cycle assessment, and logistical strategies for large-scale implementation. Through collaboration among designers, engineers, and policymakers, repurposing strategies such as the one proposed here can help transform renewable energy waste streams into valuable resources for sustainable urban development.

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Sustainable Design and Assessment of an Innovative Prefabricated Aluminium Modular Building System

Christos Katsaros, Themistoklis Nikolaidis(✉), and Evangelos Efthymiou

Department of Civil Engineering, Institute of Metal Structures, Aristotle University of Thessaloniki, Thessaloniki, Greece
thnik@civil.auth.gr

Abstract. The aim of the present study is to investigate the operational and seismic behaviour of an innovative, modular, two-story prefabricated residential modular building made of structural aluminium. More specifically, it concerns an approach in optimal designing of a sustainable and energy-efficient aluminium building system, with regards to their structural performance, easy assembly and disassembly, low cost and preconstruction. The structure as a whole was simulated and estimated using Dlubal RFEM software package and the critical assembly joints of beam-to-column and the column base respectively was simulated using IDEA StatiCa and ANSYS software packages in accordance to Eurocodes framework. The load-bearing system, made of aluminium alloy columns, beams and joints and orthotropic aluminium deck slabs. Lateral stiffness against horizontal loads is ensured by a combination of Moment Resisting Frames MRF and cable X-bracings made of stainless-steel. The critical assembly joints of the prefabricated parts were designed with the aim of avoiding impractical on-site welding and enabling disassembly/reuse. Solutions are proposed for demountable bolted connections using specially formed galvanized steel parts. The verification of individual joint components was carried out using finite element analysis software packages. The structural performance shows an optimal design including the effectiveness of the proposed connection system for the safe transfer of loads. The proposed system can lead to lightweight buildings that are structurally sound, economically competitive, and environmentally sustainable, making them suitable for broad future application in construction.

Keywords: Structural Aluminium · Prefabricated Modular Building · Critical assembly joints · Sustainable Optimal Design · Lightweight structures · disassembly

1 Introduction

Aluminium is a material that is still rare in its use as a load-bearing structural element material [1], The density of aluminium is approximately 1/3 that of steel: aluminium, therefore this is its most attractive feature for wider use in structural and complex architectural applications. Although the production of primary aluminium requires a large

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amount of electricity, but the energy reinvested during its reconstruction requires only 3–5% of the energy consumed in primary production, so aluminium can be considered as an energy bank [2]. Modular prefabrication is a subject of research and development worldwide [3, 4], as its technology now allows the construction of increasingly complex buildings [5–7].

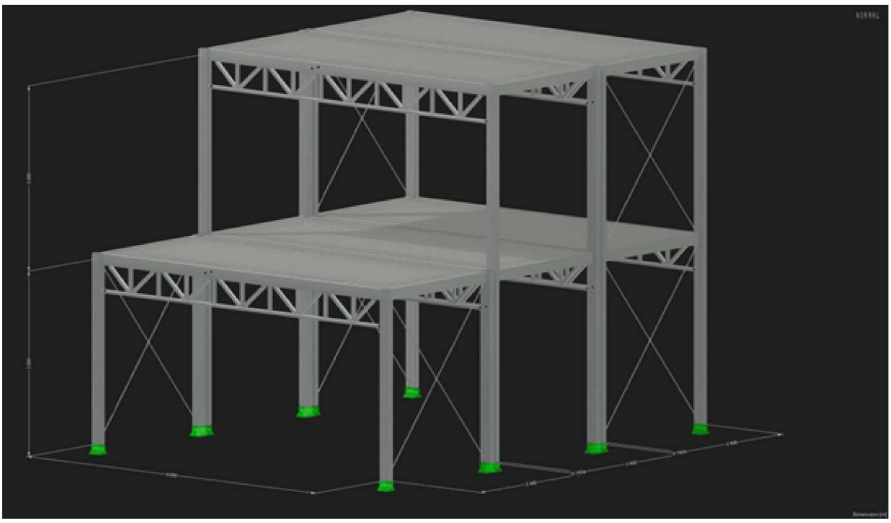


Fig. 1. 3D sketch of the load bearing system of the prefabricated modular building.

The basic concept here is to create an innovative and smart aluminium modular designed building system (see Fig. 1), which promotes fast controlled factory-made modules that are transported and bolted assembled on-site. For the purposes of this research work, an example of a two-story house consists of three prefabricated modules on the ground floor and two modules respectively on the 1st floor [8].

The most difficult part of a modular prefabricated systems is the assembly of joints [9], whether here it concerns the intra-modular connections of the modules that favor speed and sustainability, become detachable and can be carried on the construction site without on-site welding and therefore subsequent HAZ. The proposed special joints formed using an additional bolted (with galvanized bolts) connecting piece on-site, which should be designed in such a way as to remain the joint intact during the operational life, under different characteristic design limit states of the structure.

2 Resilience Design Aspects of the Modular Building System

In order to achieve a sustainable and resilient structural system, during the design of a single module, was chosen rigid beam-column connections, forming Moment Resisting Frames MRF in the longitudinal direction and a combination of moment resisting frame reinforcing by vertical X Cable Lateral Bracings in the transverse direction. The external

shape of the column cross section with multiple grooves allows the optimal integration of T-head bolts together with suitable distributed holes (see Fig. 2(left)). Regarding the boundary conditions, around axis y-y columns, made by complex hollow section by extruding aluminium through a suitable shaped machine the support is considered to be fixed, while around axis z-z is considered to be hinged.

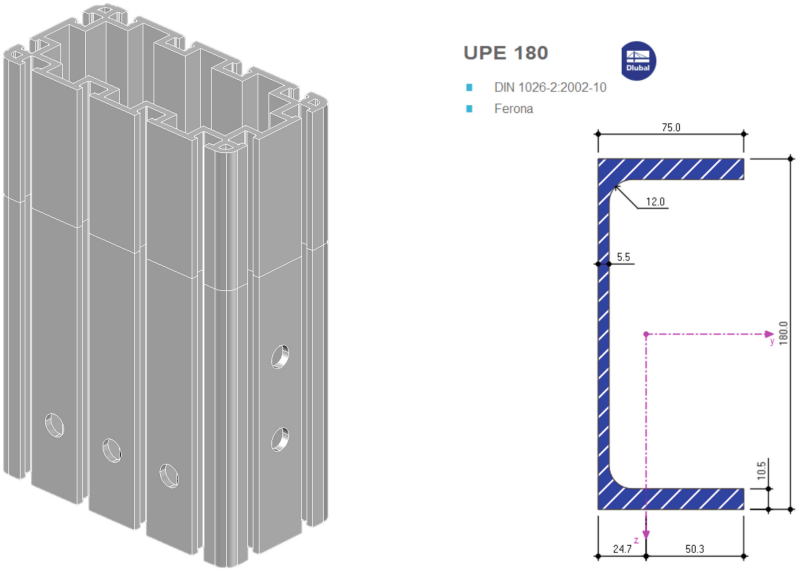


Fig. 2. 3D Sketch of the typical column cross section (left) and typical beam cross section (right).

For the Top chord of the trussed aluminium beams (truss lattice girder), it was formed by an open U-profile cross-section (see Fig. 2(right)), which would allow the recessed application of the 15 cm high orthotropic aluminium slab inside. Placing an elastomeric sheet between the two aluminium surfaces, the inner surfaces of the beam flanges and the orthotropic plate, can effectively reduce slab vibrations. Moreover, the rest of a smart lattice girder (see Fig. 3), formed by SHS truss member sections. The design of the aluminium deck floor is designed to avoid vibrations [10], by exploiting the technologies of extrusion and friction welding. With the aim to avoid corrosion phenomena and to decrease the total structural weight and the need for maintenance, stainless steel X wire ropes that forms light unilateral diagonal prestressed bracing members (working only in tension), are added to the final structural system.

3 Sustainable and Circular Design Assessments

Since aluminium was first utilized in civil engineering projects, many aluminium alloy structures have been in use and are approaching a large volume of incoming wastes. Recycling these wastes to forming new structures significantly reduces energy consumption and carbon emissions, while the basic properties of the material generally remain

unchanged during recycling. Comparing aluminium with steel, it turns out in one hand that it's an expensive material as its production cost is at least 50% more expensive than that of steel.



Fig. 3. 3D Sketch of the Modular aluminium prefabricated building.

The structural elements of the proposed modular construction (see Fig. 3) are choused, in order to be realized a manufacturing and easy assembly building system with small impact to the total material weight. By this, the amount of circular and recycled elements is maximized and the use of reinforced concrete is limited only to the foundation. Moreover, the non-bearing elements of the building include wood laminate floor covering, suspended gypsum ceilings, light gypsum internal partition walls, perimeter external double shell aluminium claddings with thermally insulating rockwool boards inside. On the other hand, taking into account the lower total weight of the structures, as well as their resistance to corrosion in particularly adverse environments, ultimately under a modular design project, this load-bearing aluminium structure can be created at a similar cost or even lower than that of a steel structure [11].

4 Design of Critical Joints by Numerical Nonlinear Analysis

Two special joint pieces are designed using additional hollow elements of S275 galvanized steel. To avoid plasticizing phenomena of internal members of the special steel connection pieces, during critical design loads, it was simulated in IDEA StatiCa software as independent members (see Fig. 4). The dimensions of these pieces were additionally defined with the aim of passing internally the aluminium columns and beams as configured in the system.

The special piece intended for the column base joints consists of a 15 mm thick base plate to which the 10 mm thick rectangular piece is welded centrally, from the inside

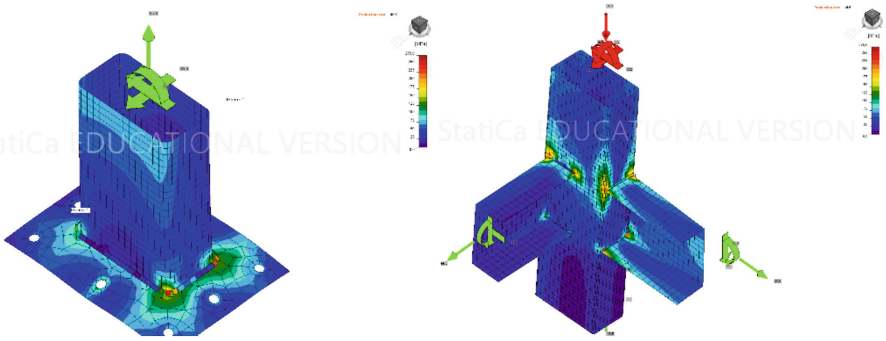


Fig. 4. Critical von-Mises stress distribution of special internal joint pieces of base (left) and column-to-beam (right).

of which the aluminium column is "digested" to be connected to it via longitudinal M16/8.8 bolts (through-bolts). The connection of the base plate to the foundation will be made using hook-end steel anchor bolts. Similarly, the special piece intended for the 3D column-to-beam joints consists of the same shape 10 mm thick rectangular piece welded to connected plate pieces.

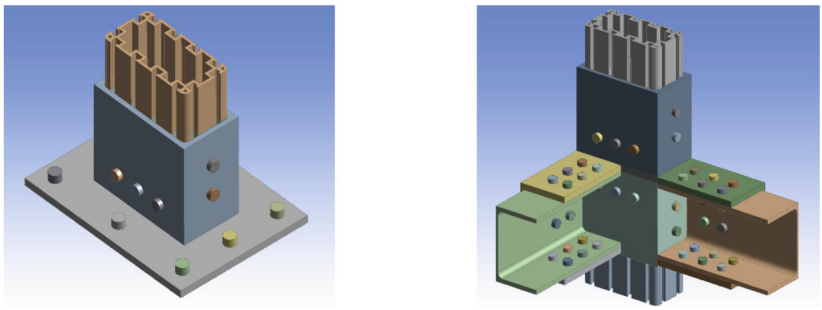


Fig. 5. Discretized model of a typical base joint model (left) and a typical column-to-beam joint model (right).

Additionally, two special joints of a) a typical base joint and b) a typical column-to-beam joint, was simulated in details separately in ANSYS software (see Fig. 5). All contacts were chosen to be simulated as nonlinear frictional contacts, with a coefficient of effective friction $\mu = 0.2$ between metal surfaces.

For all contacts, symmetric behaviour is also activated, which prevents the interpenetrating of the mesh joints of the two surfaces in contact [12]. The consider contacts between bodies surfaces where was consider the bodies involved are in contact from the beginning, was also activated the adjust to touch option, in order to facilitate the computer analysis and to avoid penetration and large gap problems. This was not was taken only in the case of contacts at the base joint, because this is not realistic and additionally, the step and the amount of sharp contact between column section and steel piece is of

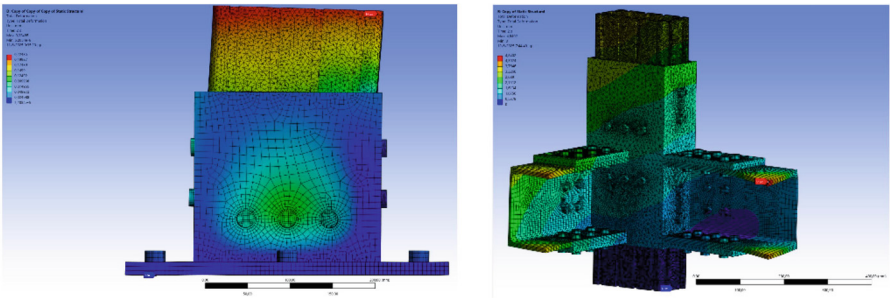


Fig. 6. Critical von-Mises stress distribution on base complex joint (left) and on column-to-beam complex joint (right).

high interest. For the lower side of the base plate, the non-linear compression-only support option was defined, which only restrains the vertical compressive-negative stresses, together with restraints at the base of the anchors that simulate their restraint due to their encasement in the concrete box. All stress and displacement results indicate adequate bearing capacity and safety (see Fig. 6). The critical points on this time-cost analysis were the marginally sufficient of some specific longitudinal bolt holes, because they are extremely forced by the receiving moments from the joint to the column.

5 Numerical Analysis of the Assembled Modular Structure

The fully assembled modular structure was simulated using Dlubal RFEM software taking into account all the critical details that come from the detailed analysis with specific simulations at the joints. Due to the assembly method the internal columns become with double cross-sections by placing special connecting pieces (in three positions) along their height. In this way, the buckling resistance of these columns is significantly increased, by making a typical bundle column member with parallel elastic sections in contact [13]. Moreover, the vertical displacements of the light composite floors (see Fig. 7(left)), $u_{max} = 3.32$ mm $< L/360 = 6{,}94$ mm and the critical horizontal displacements (see Fig. 7(right)), $v_{max} = 9{,}74$ mm $< H/150 = 20$ mm, at SLS, satisfies the strictest design limits for sensitive structures with composite floor systems like this.

Regarding seismic response of the building using Dlubal RFEM software, the assessment was derived from a linear analysis using eigenvalue analysis (see Fig. 8) and elastic spectra according EN1998–1. Moreover the evaluation of the of the hysterical behaviour of the structure was derived by the same software from a nonlinear Pushover analysis.

A Stress-Strain analysis was also performed for all aluminium members, linear and area ones (at ULS and Seismic Design States), with a limit check to maintain equivalent von-Mises stresses below the conventional yield limit of 0.2% (stress-strain analysis Add-On).

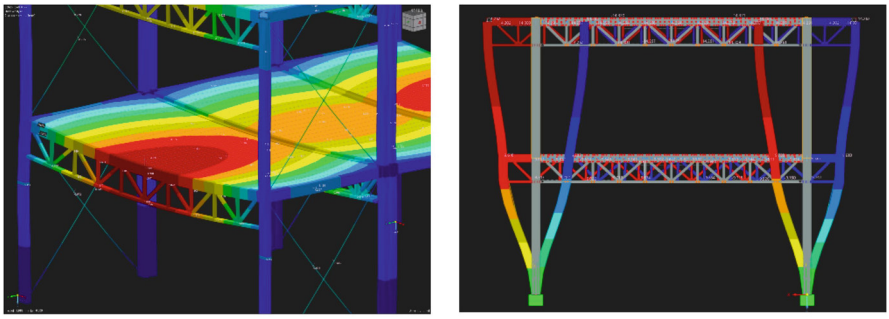


Fig. 7. Vertical(left) and horizontal (right) critical floor displacements at SLS.

Mode No.	Modal Mass M [kg]	Effective Modal Mass - Translational Direction [kg]			Effective Modal Mass - Rotational Direction [kgm²]			Factor for Effective Modal Mass - Translational Direction [--]			Factor for Effective Modal Mass - Rotational Direction [--]		
		m_{eqX}	m_{eqY}	m_{eqZ}	m_{eqX}	m_{eqY}	m_{eqZ}	f_{meqX}	f_{meqY}	f_{meqZ}	f_{meqX}	f_{meqY}	f_{meqZ}
1	5451.4	12160.7	0.0	0.0	0.00	2248.62	4043.80	0.893	0.000	0.000	0.000	0.091	0.033
2	2806.8	0.0	12577.2	0.0	1818.52	0.00	0.00	0.000	0.923	0.000	0.073	0.000	0.000
3	3635.4	563.8	0.0	0.0	0.00	1417.56	111973.00	0.041	0.000	0.000	0.000	0.057	0.910
Σ	11893.6	12724.6	12577.2	0.0	1818.52	3666.18	116017.00	0.934	0.923	0.000	0.073	0.148	0.943
Σм		13624.8	13625.0	0.0	24808.00	24805.50	122989.00						
%		93.39 %	92.31 %		7.33 %	14.78 %	94.33 %						

Fig. 8. Total perc. of participating masses of the structure per degree of freedom.

6 Conclusion

The main conclusions of this research analysis were:

- High load-bearing capacity of aluminum hollow and open cross-sections by a smart combining of the appropriate structural members and the useful and optimal form of the connection joints.
- The performance and operation of the orthotropic slab was optimal. Indeed, this aluminium plate, exhibited excellent stress and strain behavior, confirming its suitability for structural building applications.
- The proposal of galvanized steel pieces at the bases of columns and at column-to-beam joints demonstrated reliable load reception and redistribution, while simplifying construction and assembly, without significant yielding areas and plasticization in the numerical simulations.
- This research deserves to be continued with the integration of laboratory experimental tests to confirm the optimal numerical results.

It follows that in the context of achieving a circular economy, the state deserves to help and finance the competitiveness of prefabrication and research into structural aluminum applications in Greece. It is clear that the proposed system can lead to lightweight buildings that are circularity sound, economically competitive, and environmentally sustainable.

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Advancing Concrete Circularity: From Deconstruction to Cascading Valorisation Coupling Reuse and Recycling Approaches

Emilie Du Mortier(✉) and Emilie Gobbo

Louvain Research Institute for Landscape, Architecture and Built Environment (LAB), Université catholique de Louvain, B-1348 Louvain-La-Neuve, Belgium
emilie.dumortier@uclouvain.be

Abstract. Concrete is one of the construction materials with the highest environmental impact, mainly due to CO_2 emissions associated with cement production. Recycling through selective demolition remains the most common recovery method. Still, it mostly leads to downcycling: it reduces the need for virgin aggregates without significantly reducing cement demand, the primary source of environmental harm. In this context, reusing concrete elements reclaimed through careful deconstruction represents a high-value strategy that can substantially mitigate the impact of new concrete production while aligning with the waste hierarchy. However, despite growing interest, research remains fragmented and only partially documents recovery and reuse processes. This study conducts a structured analysis of the literature to examine how research addresses the concrete reuse process, focusing on categorizing scientific studies according to their coverage of the different reuse process stages and providing an overview of implemented case studies documented in scientific research. The mapping reveals three key gaps in scientific research: limited investigation of reclamation practices, a lack of large-scale implementation studies, and the strong yet understudied influence of donor building characteristics on both reclaimed element typologies and their potential valorisation. To address these challenges, future research should develop a more detailed analysis of the literature to precisely identify how the reclamation phase is currently addressed in studies. This refined examination will also help identify gaps in the current research landscape, providing clearer insight into how the reclamation phase is conceptualised and identifying areas requiring further investigation.

Keywords: Concrete · Reuse · Recycling · Deconstruction · Circular economy · Reclamation

1 Introduction

Concrete manufacturing accounts for 8 to 9% of global anthropogenic CO2 emissions and 2 to 3% of energy consumption [1]. In Europe, concrete accounts for approximately 30% of waste flows in the construction sector, including 5 million tons annually in Belgium alone. It is projected that annual cement production could increase by an additional

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50% by 2050, underscoring the urgent need to develop solutions to integrate concrete into a circular economy [2].

The most widely adopted solution is the recycling of concrete aggregates, which reduces the need for raw material extraction. However, producing concrete with recycled aggregates still requires cement clinker–the most CO_2-intensive material due to its calcination process (65%) and fuel combustion (35%). This often leads to downcycling, particularly in application such as road construction or backfill.

Furthermore, conventional recycling does not fully align with the waste hierarchy set out in the EU Waste Framework Directive. In this context, the reuse of concrete elements reclaimed through careful deconstruction represents a high-value strategy that can substantially mitigate the environmental impact of new concrete production while aligning with the priority levels of the waste hierarchy.

Unlike crushing, reuse involves integrating existing concrete elements into new construction while preserving their formal integrity as well as their technical and architectural qualities, thereby extending their lifespan [3]. Research shows that reusing concrete elements can considerably reduce carbon emissions and energy consumption during the product phase– by up to 93% and 98%, respectively– compared to new production or recycling [4].

While concrete recovery is increasingly recognized as a sustainable practice, reuse implementation remains fragmented across isolated case studies and technical reports [5]. This fragmentation reveals a critical research gap: the absence of a structured overview of which phases of the concrete reuse process are addressed in scientific literature. To address this gap, this study combines a systematic literature review with an analysis of pilot projects. It provides a holistic view of the concrete reuse value chain, from potential reuse evaluation to the reclamation of concrete elements and then their reintegration in new projects.

2 Scope

This study examines research focusing exclusively on the reuse of concrete elements from buildings not originally designed for dismantling or deconstruction–including both precast and cast-in-place concrete. The scope excludes research on non-concrete structural elements, elements from buildings designed for disassembly, and applications primarily intended for recycling.

3 Methodology

3.1 Systematic Literature Review

A systematic literature search was conducted across Scopus (for its rigorous indexing and reproducibility) and Google Scholar (for its broad coverage, including grey literature), following PRISMA guidelines, as shown in Fig. 1. This dual-database approach initially identified 598 records, of which 105 studies were retained after applying predefined eligibility criteria, as illustrated in Fig. 1.

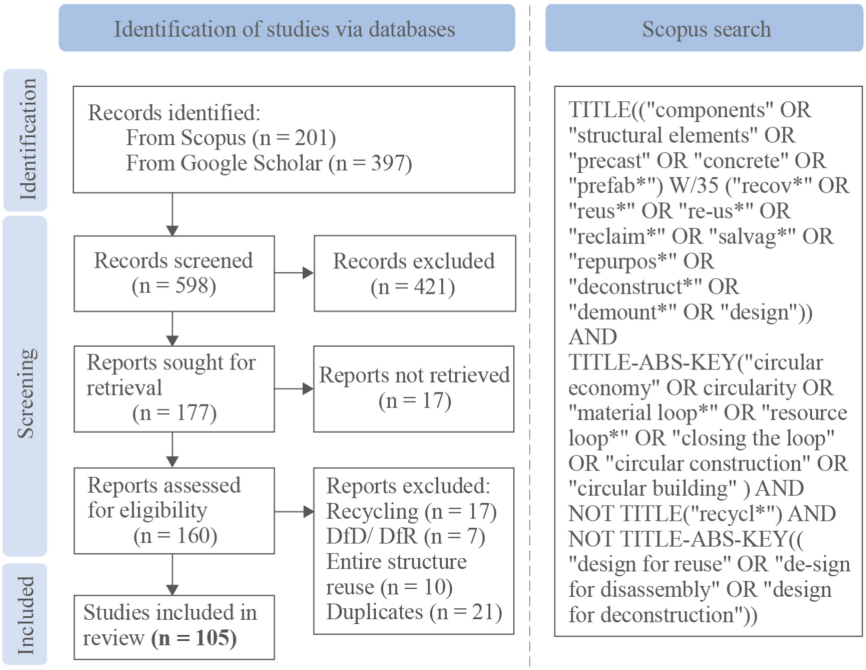


Fig. 1. PRISMA screening for Literature review

3.2 Classification of Literature Review

The literature review was systematically categorized according to the key stages of the concrete element reuse process, as defined by Huuhka et al. [4] and illustrated in Fig. 2:

1- Pre-Deconstruction Audit – Feasibility studies assessing remaining service life, structural capacity, and technical criteria.
2- Deconstruction Planning – Research developing inventory-based structural and practical deconstruction plans, ensuring safe and efficient dismantling.
3- Deconstruction/Dismantling – Studies proposing tools, frameworks, or methodologies to optimize technical operations (e.g., sawing, lifting).
4- Transport to Interim Storage – Research addressing logistical optimization of materials flows, including transport and storage strategies.
5- Quality Assurance & Refurbishment – Studies emphasizing the documentation and certification of reused components, ensuring compliance verification, and adaptation when necessary.
6- Design of a New Building – Research developing innovative approaches for integrating reclaimed concrete elements into new construction projects, focusing on design strategies and mounting solutions.
7- Construction of the New Building – Research documenting implemented case studies or prototypes that demonstrate practical applications of concrete element reuse

In addition to these process stages, the review identified four cross-cutting dimensions that influence the entire reuse value chain: Managing information digitally (e.g., BIM, QR code for tracing), structuring conditions (e.g., enablers & barriers, political/legal frameworks), dynamic mechanisms (e.g., stakeholder interactions, knowledge exchange), and measurable outcomes (e.g., environmental, economic, and social impacts, as well as value creation across the chain).

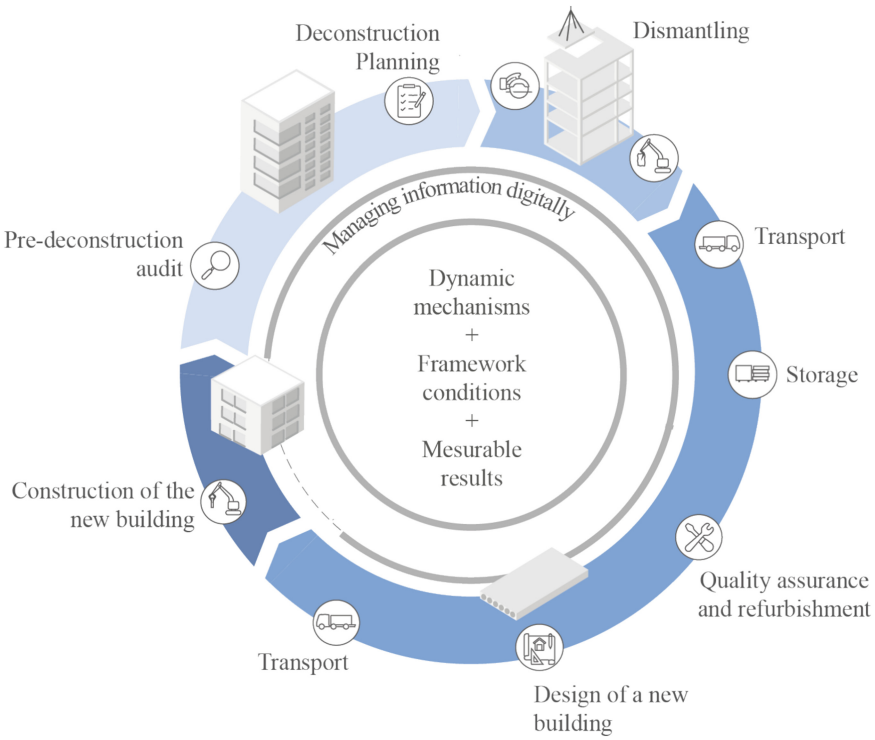


Fig. 2. The process of concrete element reuse

3.3 Analysis of Implemented Projects

The implemented projects were categorized using three key criteria. The first criterion characterizes the nature and context of reuse, including donor building characteristics–particularly the mode of concrete placement (cast-in-place or precast), which significantly influences the reclamation process. It also classifies the typologies of reclaimed elements, as in [6] (3D assemblies, elements including panels and linear elements, blocks, rubbles, and irregular debris), and according to the case study analysis. Valorisation levels (equivalent reuse, downcycling reuse, and upcycling reuse) are defined using the definitions proposed by Küpfer et al. [5].

The majority of projects analysed originate from two key sources: "Atlas for Reused Concrete" by Küpfer et al. [7], and the original collection of 77 PRECS (Piecewise

Reuse of Extracted Concrete in new Structures) projects documented by Küpfer et al. [5], which were implemented between 1967 and 2022 across Europe and the U.S.A.

4 Structured Mapping of Implemented Projects and Scientific Studies

4.1 Delimitation of Reclamation and Integration Processes

The mapping, as shown in Table 1, reveals a significant disparity in research coverage: Design is addressed in 33 studies, compared to 6 studies on dismantling only. While some studies only mentioned the reclamation process as a preliminary step without analyzing it or providing methodological, experimental, or conceptual contributions to this stage, the integration dimension remains the primary aim of most studies [8–12].

Several studies [9, 10] describe initial design phases, propose configurations incorporating reused concrete elements, and evaluate their technical feasibility– though primarily within the context of prototype development research rather than large-scale implementation.

Table 1. Distribution of concrete reuse studies by process stage

Stages of the concrete element reuse process	Example of an Article	Scopus total	Google Scholar total	Total both databases
Pre-deconstruction audit	X	21	12	33
Deconstruction Planning		2	2	4
Dismantling		4	2	6
Transport to interim storage		1	0	1
Quality assurance & Refurbishment	X	9	10	19
Design for a new building	X	20	13	33
Construction of the building	X	11	5	16
Managing information digitally	X	10	7	17
Dynamic mechanisms		6	2	8
Framework conditions		2	9	11
Mesurables results	X	27	11	38

4.2 Nature and Conditions of Reuse Concrete Elements

In most studies, donor building characteristics and reclaimed element typologies emerge as two interdependent dimensions, both closely tied to the specific context of each case study. For instance, research on prefabricated concrete structures —which represent the majority of documented cases—typically distinguishes between two primary reclaimed element types: linear elements (such as columns, beams) and panels (including walls, facade panels, hollow-core slabs). As illustrated in Table 2, these two typologies are predominantly associated with cases of equivalent reuse.

In contrast, buildings constructed using cast-in-place concrete —less commonly and primarily analysed in prototype-based reimplementation studies—typically yield smaller element typologies, such as blocks or rubble, though they may also generate 3D assemblies in certain cases. The smallest elements are most frequently documented in downcycling reuse applications, including flooring or street furniture [13], or in hybrid configurations combined with other structural materials—particularly metal—as demonstrated by several prototypes developed in Switzerland [9]. On the other hand, 3D assemblies offer the most effective reuse, preserving structural and architectural integrity for significant upcycling potential—even compared to new equivalents [14, 15].

Table 2. Element-Specific reuse outcomes in pilot projects

Donor	Placement mode			Type of elements (per project)		Receiver		Valorisation		
	PC	CIP	Both			Protot.	Case Studies	↘	=	↗
64	35	8	3	A	2	2	1			2
				E	51	8	47		48	2
				B	11	5	6	9	1	1
				R	2	1	1	1		1
				I	1	0	1	1		
64						**16**	**57**	**11**	**49**	**6**

PC: precast concrete, CIP: cast-in-place, A: 3D assemblies, E: Elements, B: Blocks, R: Rubbles, I: Irregular debris, ↘ Downcycling reuse, Equivalent reuse, ↗ Upcycling reuse.

5 Discussion

The structured mapping of studies and projects reveals two main limitations in current research on concrete reuse.

1. Insufficient scientific research on reclamation practice

   Reclamation represents a complex and decisive process that remains largely under-theorised. Scientific articles typically only treat them as preliminary steps.

This asymmetry reveals a structural gap in literature: the absence of a comprehensive scientific framework for analyzing, comparing, and standardizing reclamation practices.

2. Limited large-scale implementation

   The predominance of small-scale prototypes —particularly for elements reclaimed from cast-in-place buildings—constrains the assessment of concrete reuse at scale. As [16] has already pointed out, without large-scale implementation, the sector cannot assess the feasibility, economic viability, or logistical challenges of widespread adoption.

The analysis of implemented projects reveals the significant yet understudied influence of donor building characteristics on concrete reuse outcomes. Current research typically examines element typologies (such as 3D assemblies, elements, blocks, rubble) as isolated technical examples rather than components within a systematic valorisation hierarchy. However, the valorisation potential depends on complex interactions between donor building characteristics, reclamation methods, and element typologies – relationships that are rarely investigated in combination.

6 Conclusion

This study identifies three critical research gaps that currently hinder concrete circularity: (1) insufficient scientific investigation of reclamation practice, (2) limited large-scale implementation studies, and (3) the absence of a tailored valorisation hierarchy for concrete reuse.

To address these challenges, a more detailed analysis of the literature is needed to precisely determine how the reclamation phase is currently addressed in existing studies. This refined examination would help expose gaps in the current research landscape, providing clearer insight into how the reclamation phase is conceptualised and pinpointing specific areas requiring further investigation.

These limitations raise fundamental questions about the barriers embedded in current deconstruction practices that hinder wider adoption of concrete reuse. Rather than requiring a radical transformation of existing practices, this transition could be achieved through more controlled, incremental implementation approaches.

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Closing the Circularity Gap in Sustainability Protocols: A Theoretical Reframing for Adaptive Reuse in the Built Environment

Marco Delli-Paoli[1(✉)], Maria Beatrice Andreucci[1], Philip Griffiths[2], Selin Karagözler[3], and Charalampos Baniotopoulos[4,5,6]

[1] Department of Planning, Design, Technology of Architecture, Sapienza University of Rome, 00196 Rome, Italy
marco.dellipaoli@uniroma1.it
[2] Belfast School of Architecture and the Built Environment, Ulster University, Belfast BT15 1ED, York St, UK
[3] Faculty of Architecture, Department of Interior Architecture and Environmental Design, Yaşar University, 35100 İzmir, Turkey
[4] School of Engineering, University of Birmingham, Edgbaston B15 2TT, Birmingham, UK
[5] Faculty of Civil Engineering, Leibniz University Hanover (LUH), Hanover, Germany
[6] EPFL, Lausanne, Switzerland

Abstract. Although Circular Economy has emerged as a key paradigm for sustainable transitions in the built environment, its integration into sustainability assessment protocols remains fragmented and methodologically incomplete. Existing frameworks are largely shaped by operational performance, prioritising environmental efficiency over resource circularity. Consequently, current protocols insufficiently address structural retention, temporal adaptability, design- for-transformation, and material cycling – dimensions central to circularity in adaptive reuse. This paper reframes sustainability assessment by conceptualising circularity as a multiscalar, temporal, and systemic property of building lifecycles rather than a set of isolated material or design attributes. Drawing on circular economy theory, systems thinking and lifecycle perspectives, the study develops (i) a conceptual model positioning adaptive reuse as a regenerative process integrating material, functional, and temporal circularity, (ii) a critique of existing assessment protocols revealing implicit linearity assumptions and gaps related to long-term adaptability, embodied resource value, and future climatic conditions, and (iii) a framework embedding circularity into sustainability assessment through relational indicators capturing synergies between material retention, whole-life energy reduction, and climate-responsive adaptation and mitigation. By conceptualising circularity as a relational and dynamic construct, the study advances a lifecycle-based perspective capable of recognising the systemic value of adaptive reuse and supporting more coherent integration of circularity into sustainability assessment practice.

Keywords: Circularity Assessment · Building Adaptive Reuse · Performance-based Sustainability · Lifecycle Systems Modelling · Sustainability Evaluation Frameworks

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1 Introduction

1.1 Background: Circular Economy and the Built Environment

Circular Economy (CE) has progressively consolidated its role as a guiding paradigm for sustainability transitions within the built environment, reframing resource management from linear throughput models toward systemic value retention and regenerative material cycles [1]. Within the architecture, engineering and construction (AEC) sector – responsible for a substantial share of global material consumption, waste generation, and greenhouse gas emissions – the operationalisation of circularity has become a strategic priority for both research and policy [2].

Historically, sustainability efforts in the building sector have focused predominantly on operational energy efficiency. While this focus has delivered measurable environmental improvements, growing attention is now directed toward embodied impacts, lifecycle extension, and the long-term adaptive capacity of buildings [3]. With- in this expanded perspective, adaptive reuse of existing assets is widely recognised as one of the most effective circular strategies, enabling the preservation of embodied carbon, the extension of service life, and the reduction of demolition-related externalities [4]. Despite this recognition, the integration of circular economy principles into mainstream sustainability assessment protocols remains uneven and methodologically fragmented [5].

1.2 Problem Statement: The Circularity Gap in Sustainability Protocols

Prevailing sustainability assessment frameworks in the AEC sector continue to exhibit a strong bias toward operational-performance metrics [6]. Although these systems have significantly advanced performance benchmarking, they tend to marginalise several dimensions that are theoretically central to circularity, including structural retention, temporal adaptability, design-for-transformation, and long-term material cycling [7].

This condition produces what can be defined as a circularity gap: a structural misalignment between the systemic ambitions of circular economy theory and the predominantly linear, snapshot-based logic embedded in current sustainability protocols.

1.3 Research Aim and Questions

This research aims to critically evaluate the extent to which widely adopted sustainability assessment protocols operationalise circular economy principles relevant to adaptive reuse and to develop a relational framework capable of strengthening this integration. The investigation addresses three research questions:

RQ1. To what extent do current sustainability assessment protocols explicitly integrate circular economy principles relevant to adaptive reuse?
RQ2. How are structural retention, adaptability, design-for-transformation, and material cycling represented within existing assessment criteria and scoring systems?
RQ3. What systemic gaps emerge from the comparative analysis, and how can relational lifecycle indicators contribute to bridging these gaps?

2 Theoretical Foundations

This section outlines the theoretical foundations underpinning the study by examining key conceptual perspectives on circular economy, adaptive reuse, and systems-based lifecycle thinking in the built environment. Together, these perspectives establish the conceptual framework through which circularity is interpreted as a systemic and temporally dynamic property of building performance.

Circular Economy beyond Material Recycling. Contemporary discourse on the circular economy in the built environment is increasingly shifting its focus from waste management to strategies that preserve embodied value, slow resource flows and extend asset lifespans. Within buildings, maintaining structural components and enabling long-term functional adaptability are considered to be the most circular approaches. This perspective challenges reductionist metrics that treat circularity as an isolated material attribute, instead calling for lifecycle-oriented evaluation frame-works that can capture interdependencies across temporal and spatial scales.

Adaptive Reuse as a Circular Strategy. Adaptive reuse operationalises circularity by coordinating processes such as material retention, functional repurposing and temporal reactivation. By extending the service life of existing assets and avoiding preventable demolition, reuse strategies generate cumulative environmental benefits that build up over time. This dynamic value creation reveals the limitations of static assessment approaches and emphasises the requirement for models that can represent deferred impacts and cross-lifecycle synergies.

Systems Thinking and Lifecycle Ontology. From a systems perspective, buildings are dynamic socio-technical complexes characterised by non-linearity, path dependency and evolving performance conditions. Therefore, circularity cannot be reduced to a single metric but must be interpreted as an emergent property arising from the interactions between the material, functional and temporal subsystems. This perspective necessitates relational and temporally explicit assessment frameworks that can capture the adaptive behaviour of the built environment over time.

3 Methodology

Research Design and Analytical Strategy. The study employs a theory-building, cross-protocol comparative methodology to evaluate how contemporary sustainability assessment systems implement circular economy principles relevant to building adaptive reuse. Rather than benchmarking individual buildings, the study examines certification protocols as socio-technical artefacts that embed normative assumptions about lifecycle temporality, material value and transformation capacity. This meta-evaluative approach enables the identification of structural blind spots within assessment architectures and supports the formulation of a relational circularity framework. The methodological workflow consists of five sequential steps: (1) global protocol mapping; (2) indicator-level analytical screening; (3) semi-quantitative circularity sensitivity assessment; (4) conceptual modelling of circular adaptive reuse; and (5) formulation of relational circularity constructs.

Global Protocol Mapping. A purposive sampling strategy identified internationally influential sustainability protocols according to four criteria: (i) global diffusion and market penetration; (ii) availability of updated technical documentation; (iii) applicability at building scale; and (iv) recognised policy or certification relevance. The resulting sample includes LEED v5, BREEAM UK Refurbishment and Fit-out (RFO) 2.0 (SD216), DGNB, WELL v2, Living Building Challenge, EU Level(s), Green Star (Australia), CASBEE (Japan), BEAM Plus (Hong Kong), GRIHA (India), China GBES, Estidama Pearl Rating System, Green Mark (Singapore) and ITACA (Italy). This selection ensures geographical representativeness and methodological diversity.

Indicator-Level Analytical Screening. A structured document analysis was conducted to systematically review the technical manuals, credit catalogues and scoring structures of each protocol. The screening was guided by four analytical dimensions derived from circular economy theory and adaptive reuse literature: (i) structural retention, referring to the valuation of preserving existing structural components and embodied carbon; (ii) design for adaptability, concerning transformability, reversibility, and spatial flexibility; (iii) material cycling dynamics, including reuse, disassembly, recycled content, and material traceability; and (iv) whole-life integration, addressing lifecycle assessment, whole-life carbon (WLC) accounting, and long-term impact reasoning. For each dimension, the analysis assessed not only the presence of relevant criteria, but also their operational depth, distinguishing between narrative recognition and effective integration within certification scoring logic.

Semi-Quantitative Circularity Sensitivity Assessment. To enable structured cross-protocol comparison, a semi-quantitative ordinal scoring system was devised, ranging from 0 to 3, with intermediate increments of 0.5. The scoring system does not evaluate building performance; rather, it assesses the architectural readiness of each protocol to recognise and reward circular adaptive reuse strategies within its internal logic. Scores were assigned through cumulative consideration of three evaluative aspects: (i) the explicitness of circular or adaptive reuse requirements, (ii) the degree of methodological operationalisation and measurability, and (iii) the relative weight attributed to such criteria within the overall rating structure. The four analytical dimensions were scored independently. Table 1 shows the scoring system adopted.

Table 1. Interpretation of the 0–3 Scale.

Score	Degree of Integration	Operational Meaning
0	Absent	No reference to circular/adaptive reuse principles
0.5–1.0	Marginal	Narrative reference with minimal scoring relevance
1.5	Emerging	Recognised in measurable form but limited weight or scope
2.0	Moderate	Quantified criteria with tangible scoring impact
2.5	Advanced	Systematic integration with lifecycle reasoning
3.0	Structural	Circular logic embedded in core assessment architecture

The "Overall Gap Level" was derived from the average of the four analytical dimensions and interpreted through qualitative thresholds. It was determined that protocols with average scores below approximately 1.0 were to be classified as exhibiting a very high circularity gap. Values between roughly 1.1 and 1.5 were to be classified as indicating a high gap; between 1.6 and 2.0, a medium gap; between 2.1 and 2.5, a medium–low gap; and above 2.6, a low gap. This hybrid quantitative-qualitative approach has been demonstrated to enhance transparency and reproducibility, while preserving interpretative flexibility appropriate to theory-building research (Table 2).

Conceptual Modelling of Circular Adaptive Reuse. Building on the comparative assessment, a systems-based conceptual model was developed to reinterpret adaptive reuse as a dynamic circular process unfolding across the building lifecycle. Circular performance is framed as an emergent property arising from the interaction between *material circularity*, understood as the retention and preservation of embodied resource stocks; *functional circularity*, defined as the capacity for spatial and programmatic transformation; and *temporal circularity*, referring to lifecycle extension and resilience under uncertain future conditions. By integrating feedback loops, path dependency, and deferred environmental benefits, the model overcomes the limitations of static, attribute-based certification approaches, establishing a theoretical bridge between protocol gap analysis and assessment reformulation.

Formulation of Relational Circularity Constructs. The final methodological phase addresses a key limitation identified in existing protocols: the prevalence of single-variable indicators that fail to capture systemic interactions. Conversely, this study proposes relational circularity constructs as higher-order evaluative categories that can represent interdependencies across lifecycle variables. In this context, circular value emerges from the coordinated behaviour of material stocks, energy performance, and adaptive capacity over time.

Three relational constructs are conceptually advanced: (i) the interaction between structural retention and whole-life energy performance, highlighting how embodied carbon preservation influences long-term operational impacts; (ii) the nexus between adaptability and climate response capacity, reflecting the role of flexibility in managing environmental uncertainty; and (iii) the relationship between lifecycle extension and avoided future impacts, capturing the cumulative benefits of deferring demolition and reconstruction. These constructs are intentionally formulated as conceptual categories rather than prescriptive metrics, providing a scalable foundation for embedding adaptive reuse within next-generation sustainability assessment systems.

Table 2. Comparison of Sustainability Protocols and CE Integration for Adaptive Reuse

Protocol	KPI/Score Category	Structural Material	Retention Cycling	Adaptability	Whole-Life Cycling	Overall Gap Level
DGNB	Lifecycle value, dismantling, LCA	3.0	2.5	2.0	3.0	Low

(*continued*)

Table 2. (*continued*)

Protocol	KPI/Score Category	Structural Material	Retention Cycling	Adaptability	Whole-Life Cycling	Overall Gap Level
EU Level(s)	WLC, adaptability	3.0	2.0	2.0	3.0	Low
LEED v5 WLC	Building reuse, EPDs	2.0	1.5	2.0	2.0	Medium
BREEAM	Refurbishment pathway	2.0	1.0	2.0	1.5	Medium
Green Star	Life-cycle impacts	2.0	1.0	2.0	1.5	Medium
CASBEE	Resource efficiency	2.0	1.0	2.0	1.5	Medium
BEAM Plus	Material aspects	1.5	1.0	2.0	1.0	Medium–High
GRIHA	Resource efficiency	1.5	1.0	2.0	1.0	Medium–High
China GBES	Green materials	1.5	1.0	2.0	1.0	Medium–High
Estidama	Resource stewardship	1.0	1.0	1.5	1.0	High
Green Mark	Material efficiency	1.0	1.0	1.5	1.0	High
ITACA	Partial Lifecycle	1.0	0.5	1.5	1.0	High
WELL v2	Health focus	0.0	0.0	0.0	0.0	Very High
Living Building	Net-positive, materials	2.5	2.0	2.0	2.5	Medium-Low
Challenge						

4 Results

Comparative Circularity Performance. The cross-protocol analysis reveals marked heterogeneity in the integration of circular economy principles relevant to adaptive reuse. DGNB and the European Level(s) framework demonstrate the highest structural alignment, primarily due to systematic lifecycle modelling, explicit treatment of whole-life carbon and measurable consideration of adaptability and disassembly. Living Building Challenge shows strong philosophical consistency with regenerative principles, although its lifecycle quantification remains less structurally embedded than in DGNB. LEED v5 evidences significant progress compared with previous iterations through expanded whole-life carbon accounting and material transparency provisions;

nevertheless, operational energy continues to exert dominant influence within its rating architecture. BREEAM Refurbishment and Fit-Out, Green Star and CASBEE exhibit moderate levels of integration, addressing material efficiency while only partially operationalising adaptability and structural retention. BEAM Plus, GRIHA, China GBES, Estidama, Green Mark and ITACA demonstrate fragmented incorporation, where circular provisions remain peripheral. WELL v2 displays minimal alignment with circular adaptive reuse due to its health-centred evaluative focus.

Structural Blind Spots and Systemic Implications. Four recurrent structural blind spots emerge across the analysed frameworks. Firstly, operational energy metrics continue to dominate weightings in ratings, which constrains the relative importance of preserving embodied carbon. Despite representing the most effective strategy for maintaining embodied value, structural retention rarely receives proportional scoring relevance. Furthermore, design for adaptability is poorly operationalised and is often expressed in qualitative rather than quantifiable terms, limiting its influence on certification outcomes. Lastly, material indicators prioritise recycled content or waste diversion over the long-term deceleration of resource flows through lifecycle extension.

Collectively, these blind spots reinforce a predominantly linear evaluative paradigm that treats buildings as static artefacts rather than dynamic systems that evolve over time. The findings therefore support the idea of reframing circularity as a relational and temporally dependent property. Adaptive reuse does not emerge as just one circular strategy among many, but as the most significant circular intervention in the built environment, capable of preserving structural, material, and cultural capital simultaneously. However, current protocols insufficiently reward this systemic value.

Toward a Dynamic and Reform-Oriented Interpretation of Circularity. The relational constructs developed in Sect. 3 demonstrate that circular performance can only be coherently assessed when material retention, functional adaptability and temporal extension are treated as interdependent dimensions within lifecycle-sensitive evaluation frameworks. By shifting from attribute-based to interaction-oriented assessment logic, the proposed approach provides methodological guidance for recalibrating certification weightings, strengthening adaptability criteria, and supporting practitioners in evaluating adaptive reuse as a primary circular strategy. In performing this task, the study offers more than a mere comparative analysis of existing protocols; it provides a conceptual framework for their progressive evolution towards dynamic, lifecycle-integrated sustainability assessment.

5 Discussion and Scientific Advancement

The comparative analysis reveals that most sustainability assessment protocols remain structurally anchored in efficiency-driven paradigms, where operational energy continues to dominate rating architectures. Although circular economy language is increasingly present, embodied carbon preservation, structural retention and long-term adaptability are rarely embedded as core evaluative dimensions. Consequently, circularity is often reduced to material attributes, such as recycled content, rather than being interpreted as a systemic, lifecycle-dependent property.

Adaptive reuse emerges among the most effective circular strategies in the built environment because it preserves embodied resources, avoids demolition impacts, and maintains spatial capital over time. However, its systemic value is insufficiently rewarded within existing certification structures. The principal advancement of this research lies in reframing circularity assessment from an attribute-based model towards a relational and dynamic logic. The semi-quantitative sensitivity matrix enhances methodological transparency in cross-protocol comparisons, while relational constructs demonstrate how circular value arises from the interaction between structural retention, whole-life energy performance and adaptive capacity. This provides a theoretical and operational basis for recalibrating future sustainability protocols.

6 Conclusions and Future Research

The study confirms the persistence of a structural circularity gap across widely adopted sustainability frameworks. While some systems demonstrate emerging lifecycle integration, adaptive reuse remains peripheral in most assessment architectures. By conceptualising circularity as a relational lifecycle property, this research contributes a methodological scaffold for embedding adaptive reuse within next-generation certification schemes. Future research should prioritise empirical validation through applied adaptive reuse case studies, integration with digital whole-life carbon modelling tools, and extension of the framework to district-scale assessment, where circularity interacts with broader urban metabolism dynamics.

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Reducing Construction and Demolition Waste by Circular Use of Concrete

Gerald Lendecker[1](✉), Mathias Haase[2], Mihaela Meslec[2], Tatjana Tambovceva[3], and Maria Beatrice Andreucci[4]

[1] FH Upper Austria and IAPL, Wels, Austria
gerald.leindecker@fh-wels.at
[2] ZHAW- University of Applied Sciences, Wädenswil, Zürich, Switzerland
[3] Riga Technical University, Riga, Latvia
[4] Sapienza University of Rome, Rome, Italy

Abstract. The construction sector has a major environmental impact due to high resource consumption, energy use, and carbon emissions. Concrete, in particular, is a major contributor to GHG emissions. Increasing recycling and reuse or sourcing local materials can considerably optimizing its individual use and significantly reduce concrete's environmental footprint and improve construction sustainability. This paper presents the benefits of reusing building materials in a circular approach by reducing dependence on virgin resources and strengthening circular supply chains for reused concrete elements and recycled concrete. It will analyze national regulation and standard and their impact on reuse potential and new concrete mixes.

In this study, new methods of using recycled aggregates in concrete production are compared according to relevant standards. Benefits of reusing building materials in a circular manner are evaluated. Applied methodologies include systematic literature reviews, case studies, and life cycle assessments as developed by the COST Action CA21103 CircularB. Key results include the potential of new models for reuse of concrete, the identification of key barriers and opportunities, and the recommendations for a variety of stakeholders. The study is highly relevant as it addresses concrete's significant environmental impact and offers pathways toward greater sustainability and economic resilience.

Keywords: Circular Economy · Recycled Concrete · Construction and Demolition Waste · Secondary Materials · Standards and Regulation

1 Introduction

The construction sector is responsible for approximately 6 billion tons of CO_2 emissions [1]. Concrete is the most widely used construction material worldwide because of its durability, availability, and relatively low cost. Global concrete consumption exceeds 30 billion tons annually, making it the most consumed human-made material on Earth.

Cement production, a key component of concrete manufacturing, is highly energy-intensive and produces large quantities of carbon dioxide emissions. These emissions

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result from both fuel combustion and the chemical decomposition of limestone during the calcination process. Additionally, the extraction of natural aggregates such as sand and gravel cause landscape alteration, ecosystem disruption, and resource depletion.

Simultaneously, construction and demolition waste (CDW) represent a growing environmental challenge. CDW accounts for approximately 36% of total waste produced on Earth [2]. However, CDW also represents a valuable secondary resource that can be recovered and reused in new construction activities.

Within this context, recycled concrete aggregates and also the reuse of structural elements represent important strategies for reducing the global warming potential of concrete construction. Recycled concrete aggregates (RCA), obtained by crushing and processing concrete, have been widely investigated as a substitute for natural aggregates in new concrete production. However, not all parameters have been investigated. Under what conditions can the use of recycled concrete fines lead to an additional reduction of the GWP (Global Warming Potential)?

The objective of this study is to investigate circular approaches to concrete use in the construction sector by analyzing environmental benefits, technical challenges, and regulatory constraints associated with recycled concrete applications and concrete fines.

The study applies three main research approaches as methodology: A systematic literature review, case studies of crushed concrete fines, and Life Cycle Assessment (LCA), including a comparison of virgin versus recycled materials.

2 Literature Review

2.1 Environmental Impact of Concrete Production

Concrete production has significant environmental implications due to its large-scale material and energy requirements. Cement production alone accounts for approximately 7–8% [3] of global carbon dioxide emissions and for approximately 0.8 tons of CO_2 emissions per ton of cement produced.

2.2 Circular Economy in the Construction Sector

In the context of concrete, circular approaches include the reuse of structural elements, the recycling of demolition waste into new aggregates, and the development of closed-loop supply chains. Research indicates that adopting circular construction strategies can significantly reduce dependence on virgin raw materials while improving waste management and reducing environmental burdens.

Furthermore, circular construction encourages innovative approaches such as material passports, digital tracking of building components, and design for disassembly. These strategies enable future reuse of structural elements and facilitate the recovery of valuable materials at the end of a building's life cycle.

2.3 Reuse and Recycling of Concrete Materials

Several studies have investigated the mechanical performance of recycled aggregate concrete (RAC). While RAC may exhibit slightly lower compressive strength and higher

water absorption compared with conventional concrete, appropriate mix design and processing techniques can significantly improve performance. Advancements in recycling technologies have improved the quality of recycled aggregates, enabling their use in structural applications under certain conditions.

2.4 Existing Research Gaps

The literature review has stated three main areas of lack of knowledge

- Lack of circular supply chains
- Limited regulatory support
- Lack of detailed data of strength and durability on the use of recycled concrete fines lead

3 Regulatory Framework and Standards

Despite the environmental benefits of recycled concrete, several barriers hinder its widespread adoption in construction practice. One of the primary challenges is the lack of harmonized standards and regulatory frameworks governing the use of recycled aggregates in structural concrete. There are relevant initiatives on the European Committee for Standardization (CEN) as well as on national standardization boards to cover the topic.

Technical concerns regarding durability, variability in recycled aggregate quality, and long-term structural performance have also limited the acceptance of RAC in many regions. Differences in national standards and testing procedures further complicate the implementation of recycled concrete technologies. For example, the Swiss standard SIA 2030: 2021 (Concrete with recycled aggregates) [5] refers to the use of recycled concrete fines in Table 1.

Table 1. The potential use of recycling concrete according to Swiss standard SIA 20230:2021.

Recycled concrete class	Concrete type according to SN EN 206:2013 + A2:2021, Table NA.5 and NA.8								Pile concrete P1,P2,P3,P4
	0	A	B	C	D	E	F	G	
RC-C25	permissible				1)	inadmissible			permissible
RC-C50	permissible				1)	inadmissible			1)
RC-M10	permissible				1)	inadmissible			1)
RC-M40	permissible				1)	inadmissible			1)

Another detailed regulation for concrete fines, use of cement and durability is presented in the standard SIST EN 197-6:2023 01-Oktober-2023 (Cement-Part 6: Cement with recycled building materials) [6].

Therefore, recent research suggests that improvements in quality control, recycling technologies, and performance-based standards could significantly increase the reuse

potential of concrete materials. Future research and policy development are therefore crucial for enabling large-scale adoption of circular concrete systems.

4 Case Studies on Crushed Concrete Fines

Experimental research on crushed concrete fines indicating a strong relation between the granularity and geometry of the recycled aggregate from waste concrete and the water absorption rate.

In this study, granulometry, dry density and water absorption of one type of NA and four types of RA were examined and compared (Fig. 1).

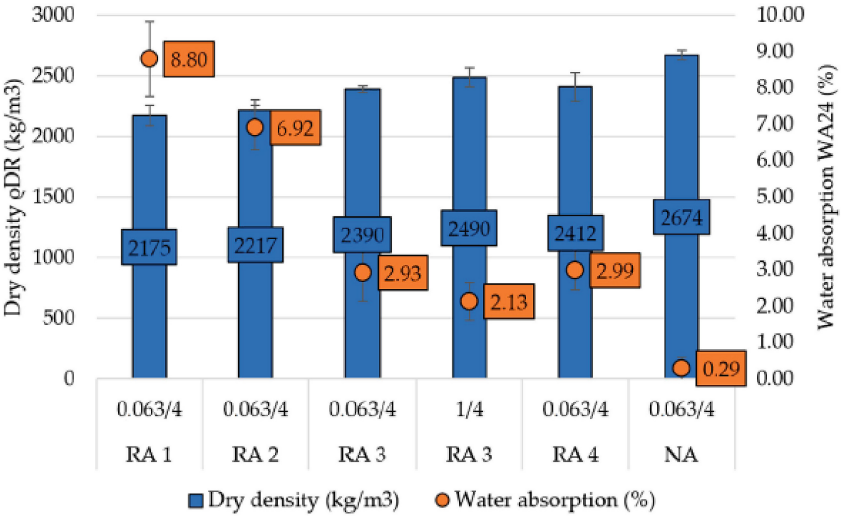


Fig. 1. Oven dry density and water absorption rate of aggregate according to CSN EN 10907–6.

All tested properties of RA differed from NA, especially the water absorption capacity, which was more than ten times higher and ranged from 2.1 to 8.8% for fine fraction of RA, where the highest water absorption was measured for RA 1 originated from waste concrete from recycling center [7].

The water absorption rate together with results in strength and durability related tests are the indicators of the cement demand for the concrete mixture when using recycled aggregates. Recent studies also focus on the geometry and on the dimension of the fines as another important indicator for the demand of cement proportion in the mix of recycled concrete.

5 Life Cycle Assessment (LCA)

5.1 Comparative LCA Results from Literature

Life Cycle Assessment (LCA) was applied to evaluate the environmental performance of different concrete production scenarios [8]. The system boundary for this study includes raw material extraction, aggregate processing, concrete production, and transportation stages.

Two scenarios were evaluated in the study: conventional concrete using natural aggregates and concrete containing recycled aggregates. In this study, two water-cement ratios (WCR) and four recycled concrete aggregate replacement rates (RCARR) were tested on two natural aggregate concrete (NAC) and six recycled aggregate concrete (RAC) samples.

A meta-analysis of recycled aggregate concrete mixes shows that environmental impacts vary depending on replacement ratio, transportation distance, and additional cement requirements [9].

These values correspond with results reported across multiple LCA investigations of recycled concrete materials. This is shown (Table 2) in comparative LCA results from literature:

Table 2. Environmental comparison of concrete production scenarios.

Concrete type	CO_2 emissions (kg CO_2/m^3)
Conventional concrete	300–350
30% recycled aggregate concrete	250–300
50% recycled aggregate concrete	220–270
Reused structural elements	<100

An evaluation of recycled concrete mixes according to further confirm that recycled aggregate concrete generally achieves **lower environmental impacts while maintaining acceptable mechanical performance**, particularly when optimized mix proportions are used and other parameters, such as optimal transport conditions are considered.

This analysis also indicates that **transportation distance and cement content are the two most influential variables** affecting the environmental performance of recycled aggregate concrete systems.

5.2 Methodologies Developed in COST Action CA21103 CircularB

In the framework of the Cost Action CA 21103 CircularB, a comprehensive method to assess the impact of transport parameters and its impact on the Global Warming Potential (GWP) for different concrete mixes using natural aggregates or recycled aggregates was developed [10]. For example, a 5% contribution of recycled concrete aggregate leads to a reduction of 4.56% CO_2 eq in the presented LCA study.

The findings indicate a relevant environmental advantage of using recycled concrete, however, it is highly context-dependent on a case-sensitive situation. Transportation distances play an important role, with the potential to turn environmental gains into losses if not considered properly.

6 Discussion

Replacing natural aggregates with recycled materials reduces resource extraction and waste generation. However, several barriers remain, including material quality variability, regulatory restrictions, and limited recycling infrastructure. Policy support, technological innovation, and improved supply chain coordination will be essential for scaling circular construction practices. Furthermore, market acceptance will be strongly influenced by quality control issues and availability of the recycled materials. Parameters such as transport distance will be a decisive factor for an overall positive impact on the GWP. This will pose a challenge to local material sourcing and circular supply chains.

7 Recommendations

For different stakeholders:

Policy Makers: Policy makers should update standards for recycled aggregates to ensure their safe and effective use in construction, and introduce incentives that encourage the adoption of circular construction practices.

Construction Industry: The construction industry should develop reuse networks that facilitate the recovery and redistribution of construction materials, and invest in advanced recycling technologies to improve the efficiency and quality of recycled construction materials.

Research: Researchers should focus on improving material testing methods to better evaluate the performance of recycled materials, and develop optimized concrete mix designs that maximize the use of recycled aggregates while maintaining structural performance in relation to strength and durability.

8 Conclusion

This study demonstrates that circular approaches to concrete use offer significant opportunities for reducing environmental impacts in the construction sector [9]. The incorporation of recycled concrete aggregates can reduce carbon emissions, energy consumption, and raw material extraction.

The optimal use of the mix of the recycled concrete and the parameters for the transports involved are important factors. Despite these advantages, regulatory barriers, technical challenges, and economic factors continue to limit widespread adoption. Future research should focus on improving recycling technologies, developing performance-based standards, and strengthening circular supply chains for construction materials.

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Structural Reuse in Seismic Regions: A State-of-the-Art Review of the Seismic Performance of Prefabricated Buildings

Igor Džolev[1(✉)], Nikola Postolov[2], Riste Volchev[2], Raluca Buzatu[3], Sofija Kekez-Baran[4], and Venla Heiskanen[5]

[1] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia
idzolev@uns.ac.rs
[2] Faculty of Civil Engineering, Ss. Cyril and Methodius University, Skopje, North Macedonia
[3] Faculty of Civil Engineering, Politehnica University Timisoara, Timisoara, Romania
[4] Faculty of Engineering and Technology, UiT The Arctic University of Norway, Narvik, Norway
[5] Civil Engineering, Karelia University of Applied Sciences, Joensuu, Finland

Abstract. The transition toward a circular built environment requires that prefabricated structural systems be conceived not only for first-life performance but also for safe and reliable second-life applications. This state-of-the-art review examines the seismic performance of prefabricated structures in the context of circular economy principles, focusing on the feasibility of reusing structural systems and components in seismic regions. The paper synthesizes experimental and numerical investigations on the behaviour of prefabricated and modular systems under earthquake loading, with particular emphasis on connection performance, damage accumulation, and residual capacity after prior service or seismic events. Studies on design for deconstruction, demountable connections, and reusable precast elements are critically analysed to clarify how circularity strategies interact with seismic performance requirements. Special attention is given to assessment and verification methodologies capable of demonstrating that reused structural elements meet target performance levels and safety margins. On this basis, the review explores whether, and under which conditions, a second life of prefabricated structures can be enabled without compromising life safety and resilience. The paper concludes by identifying key knowledge gaps, codification challenges, and research needs, and by discussing the main criteria needed to integrate seismic performance considerations into circular design and reuse decision-making for prefabricated structures.

Keywords: Prefabricated Buildings · Seismic Performance · Structural Reuse · Circular Economy

1 Introduction

Circular economy (CE) represents a transition from the conventional linear model toward a regenerative system based on closed loops of reuse, remanufacturing, and recycling. Within the construction sector, this transition implies that buildings and their components

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should be conceived so that materials remain in use at their highest possible value across multiple life cycles [1]. In practical terms, this involves extending the service life of materials through strategies such as recycling and, more effectively, direct reuse.

Applying CE principles to buildings therefore requires anticipating multiple service lives already at the design stage. In seismic regions, however, this objective introduces additional complexity, as structures must simultaneously satisfy stringent earthquake performance requirements while remaining compatible with future disassembly and reuse. Prefabricated structural systems must therefore achieve robust seismic performance during their first service life, while also incorporating design strategies that allow structural components to be safely recovered, inspected, and reconfigured. Integrating these objectives is essential for enabling structural reuse without compromising life safety and resilience and constitutes a key step toward the realization of a truly circular built environment.

Structural reuse is motivated by economic, environmental and social factors. Demolition wastes enormous embodied energy and materials, while reuse greatly cuts carbon emissions [2, 3]. Prefabricated buildings are well-suited for reuse because their components (panels, modules, frames) can be standardized and easily deconstructed [3]. In seismic regions, reuse can also improve resilience: for example, after the fire that destroyed a school in British Columbia, 75% of the original steel frame was salvaged and reused in the rebuild, dramatically reducing new material needs [3]. The remaining challenge is ensuring safety: reused buildings must still meet seismic performance targets. Therefore, integrating CE principles with seismic design is needed so that a second life can be enabled without compromising life safety and performance [4].

2 Circular Economy and Structural Reuse in the Built Environment

CE in construction aims to establish closed material loops with systems that minimize waste through recycling, reuse, and reprocessing of materials [1, 2]. A central principle of CE is the extension of material service life (e.g. steel is infinitely recyclable and its direct reuse significantly reduces resource consumption [2]). A distinction should therefore be made between extended life, where a structure continues to perform its original function through maintenance or upgrading, and second life, which implies designed recoverability, i.e., the capacity to disassemble, assess, and redeploy assets safely in a new structural configuration or location.

For prefabricated construction, second-life opportunities may arise at different scales. At the largest scale, entire buildings or modular units may be relocated and reused. Structurally, this pathway preserves not only materials but also the spatial and functional system, including the original load-path logic. In seismic regions, however, relocation may alter the seismic hazard, site conditions, and performance objectives, meaning that "second life" requires not only reinstallation but also re-verification under a different hazard and regulatory context. At intermediate scale, panels or volumetric modules may be recovered and integrated into new systems. This approach aligns with the concept of "buildings as material banks" and digital inventories that treat buildings as repositories of recoverable components [1]. Structurally, this reuse scale introduces interface challenges, as seismic performance often depends on inter-module connections, diaphragm

continuity, and the cumulative damage experienced by boundary elements under cyclic drift demands. At the smallest scale, individual beams, columns, slabs, or wall elements may be salvaged and reassigned to other structural applications. In seismic regions, however, reuse must account for prior cyclic demands, including low-cycle fatigue, cracking, yielding history, and anchorage distress, and may require sacrificing certain components to preserve the reusability of primary members. Each level of reuse involves different technical and regulatory challenges, particularly with respect to load transfer, compatibility, documentation, and verification of residual performance.

Seismic contexts pose additional uncertainty and performance demands for structural reuse. Earthquakes produce variable dynamic loads, so a reused structure must remain resilient under unpredictable seismic demands. This requires clear understanding of residual capacity after first life or any prior event. Any permanent deformations in reused members undermine this capacity. Umaraj et al. (2025) underscore that for safety, reused elements "should have no permanent deformation or change in geometry… and [offer] the same safety and reliability as an unused" component [4]. In other words, a reused building must effectively behave like new one from the standpoint of seismic codes. In practice this means damage-free disassembly, or else reconditioning of elements to restore strength. It also means adopting appropriate safety factors.

Despite the advantages of reuse, significant barriers remain. Implementing reuse requires new engineering assessment methods, reliable documentation of structural performance, and market confidence in reused components [3]. Uncertainty in seismic demand and in the history of reused components also mandates conservative design and rigorous assessment for any second-life use.

The working hypothesis is that prefabricated systems can be conceived from the outset to achieve dual performance: safe first-life operation and reliable second-life reuse. Integrating circularity strategies during the design phase enables prefabricated buildings to be prepared for future disassembly using modular dimensions and demountable connections [3, 5]. Experimental studies have shown, for example, that steel structures equipped with interlocking, demountable column bases can retain their load-bearing capacity across multiple reuse cycles [3, 5]. The long-term feasibility of this approach depends on design choices such as standardized spans to facilitate the interchangeability of reused modules and clear documentation of component properties through material passports [1]. The goal is to achieve resilience in first life and then require only minimal adjustments for second life. In practice, this might mean designing components to higher initial standards or providing post-dismantling refurbishment steps.

3 Prefabricated Structures in Seismic Regions: Systems and Failure Mechanisms

Prefabricated buildings used in seismic regions may generally be classified into four broad typologies: precast reinforced concrete (RC) frame systems, precast wall-panel systems, modular volumetric systems, and hybrid systems combining prefabricated and cast-in-situ components [6]. Structural assemblies may consist of linear elements (columns and beams), planar elements (slabs and walls), or spatial volumetric modules. Classification is generally based on the type of vertical load-resisting system and the mechanism used to ensure lateral stability.

Precast RC frame systems, composed of prefabricated beams and columns with moment-resisting or semi-rigid beam-column connections, are widely used, particularly in parking structures and commercial buildings. Precast wall-panel systems are extensively used in residential construction [6]. Hybrid prefabricated systems, combining precast gravity frames with cast-in-situ cores or shear walls, are commonly used to enhance global stiffness, ductility, and seismic reliability. In industrial construction, precast portal frame systems with cantilevered columns and simply supported beams are prevalent in Mediterranean countries, although past earthquakes have highlighted vulnerabilities associated with connection detailing and loss of support. Finally, modular volumetric systems, composed of three-dimensional prefabricated units connected at floor and wall interfaces, are increasingly used where seismic performance depends on the collective interaction of modules and the integrity of inter-module connections and diaphragms.

Across all types, seismic performance is predominantly governed by connection behaviour rather than by the strength of individual members. Field observations following major earthquakes and analytical investigations of precast industrial buildings show that column bases, beam-column joints, diaphragm interfaces, anchorage regions, and seating supports frequently control collapse mechanisms and damage propagation [7]. Typical failure modes include joint shear failure, brittle anchorage rupture, loss of seating support, insufficient tie forces, diaphragm discontinuities, and inadequate confinement.

Experience from past earthquakes, as well as findings from experimental and numerical studies, has shown that prefabricated structures often exhibit damage concentrations at connections rather than in primary load-bearing members. Common deficiencies include inadequate diaphragm continuity or slab-to-beam anchorage [7], loss of seating and insufficient mechanical continuity between hollow-core units and supporting beams [8], inadequate detailing, insufficient confinement, and weak lateral load-resisting systems [9], diaphragm cracking and seating vulnerabilities due to beam elongation and displacement incompatibility [10], failures of friction-based beam-column and roof connections [11].

From a circular-economy perspective, second-life suitability depends on whether seismic damage is (i) localized, (ii) inspectable, and (iii) repairable without compromising global stability. Systems designed with ductile, capacity-protected connectors or replaceable dissipative zones exhibit greater reuse potential than systems relying on brittle anchorage or minimal seating length. Residual drift and connection deformation capacity therefore emerge as decisive performance indicators not only for life-safety verification but also for reuse feasibility.

Overall, prefabricated systems are not inherently less suitable for seismic regions; rather, their reuse compatibility depends on connection philosophy, redundancy, diaphragm integrity, and the concentration pattern of damage.

4 Assessment and Verification Methodologies for Reused Structural Elements

The safe reuse of prefabricated structural elements in seismic regions requires a rigorous assessment framework capable of addressing both conventional existing-structure concerns and reuse-specific uncertainties. Existing standards and guidelines, including

ISO 13822, EN 1998–3, and ASCE/SEI 41–23, provide a valuable basis for evaluating the seismic performance of existing buildings. However, these documents do not explicitly address the certification and qualification of reused prefabricated components or the implications of prior service history for second-life structural use. Studies on structural reuse therefore emphasize the need to complement existing-building assessment procedures with reuse-specific inspection and documentation protocols [12].

A reuse-oriented assessment process generally involves four interrelated stages. The first stage is inspection and documentation, which includes identification of the structural system, review of available drawings and records, visual condition assessment, and examination of joints and support regions. The second stage is testing and material characterization, carried out where uncertainty exists regarding geometry, reinforcement, mechanical properties, durability, or damage state. The third stage is structural analysis, in which the system is evaluated under the relevant load combinations and seismic actions, with explicit consideration of connection behaviour, diaphragm action, degradation, and possible prior damage. The fourth stage is decision-making, through which components or assemblies are classified for direct reuse, reuse after repair or strengthening, repurposing for lower-demand applications, or recycling. When entire prefabricated buildings are considered for reuse or relocation, assessment must also include system-level verification of diaphragm continuity, load transfer between structural sub-systems, and robustness against progressive collapse.

Experimental investigations on prefabricated and hybrid systems show that seismic response is often governed by the behaviour of connections rather than primary structural members. Damage tends to be localized in beam-column joints, diaphragm connectors, or slab seating regions, while the main elements remain largely undamaged. Experimental tests on precast wall systems with energy-dissipating devices have demonstrated stable cyclic behaviour and limited residual drift, suggesting that structural damage can be concentrated in replaceable components [13]. This capacity-protected design philosophy is particularly relevant for circular-economy strategies, as prefabricated elements may retain sufficient residual capacity for reuse if damage remains confined to replaceable components. Consequently, demountable and replaceable connection systems have been proposed to enhance both seismic resilience and reuse potential of prefabricated structures.

Despite recent progress, important methodological gaps remain. There is currently no standardized damage-state classification for prefabricated connections in the context of reuse certification, and most seismic assessment procedures focus on single-event performance rather than cumulative loading histories. In addition, existing standards provide limited guidance for proof-testing salvaged connectors or diaphragm interfaces, which often control the seismic performance of prefabricated systems. Developing standardized inspection procedures, degradation models for multi-event seismic exposure, and certification protocols for reusable components will therefore be essential for enabling safe structural reuse in seismic regions.

5 Case Study: Finish Prefabricated Structures and Second-Life Potential

A practical illustration of the challenges and opportunities of second-life use is provided by a residential complex in Joensuu, Finland, investigated within the Interreg Aurora project EU-MAT. The complex consists of three residential buildings constructed in 1985 using load-bearing prefabricated concrete (PC) wall elements and semi-precast floor systems. Each structure has a transversal system of load-bearing prefabricated wall elements and reinforced semi-precast floor system (beam-and-block floor) on three levels. The case was examined in the context of planned demolition, with the objective of evaluating whether selected structural elements could be directly reused or alternatively recycled as concrete aggregate.

The assessment process began with the collection of available documentation, followed by visual inspection and in-situ verification of geometry and condition. Particular attention was paid to cracking, moisture exposure, deterioration of seams and joints, and signs of freeze-thaw damage. Additional investigations included non-destructive testing and extraction of material samples in order to determine concrete strength, density, and durability-related properties. Screening for contaminants was also necessary, since the presence of hazardous substances may restrict both reuse and recycling options.

The case study revealed several barriers that are representative of current practice. Direct reuse of PC elements requires selective dismantling to avoid damage during demolition, but such procedures are more time-consuming and costly than conventional demolition methods. In addition, the absence of standardized re-certification procedures for reclaimed structural elements creates uncertainty and often necessitates extensive testing before reuse can be considered. Under present regulatory and market conditions, recycling into recycled concrete aggregate is therefore more readily achievable than direct structural reuse. Namely, in Finland and Scandinavian countries only concrete hollow-core slabs can be re-certified relatively easily, without significant cost increase. Re-certifying prefabricated wall elements is only possible after performing extensive tests that would prove their load-bearing ability and serviceability.

The Joensuu case demonstrates that second-life use of PC elements is not solely a technical issue, but also one of process integration, documentation, and early planning. The EU-MAT case study and other circular construction projects taking place across Finland such as ReCreate [14] may provide significant insight into the possibilities, as well as the challenges that may arise during such activities.

6 Conclusions

Enabling structural reuse in seismic regions requires formalizing the interaction between circularity and seismic performance criteria. Prefabricated systems offer important advantages for circular construction because of their modularity, repeatability, and potential for disassembly. However, these characteristics alone do not ensure reuse potential. In seismically active regions, second-life applications must be supported by robust evidence that reused elements and systems can satisfy target performance requirements without compromising life safety (including damage limitation, replaceable energy-dissipating elements, and verification of residual capacity).

Three conditions emerge as particularly important. First, the structural system must be sufficiently documented and inspectable, so that its geometry, material properties, detailing, and service history can be established with confidence. Second, damage must be either absent or limited to forms that are detectable, localized, and compatible with repair or controlled reuse. Third, the reused configuration must be verified through appropriate assessment methods that consider not only member resistance, but also connection behaviour, diaphragm action, robustness, and cumulative damage effects.

Advancing circularity in seismic design requires research on performance validation and new code provisions. As prefabricated buildings become more common, creating clear verification workflows and embedding them in standards will be crucial for safe reuse in seismic regions.

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Fire Safety of Buildings: The Role of Combustible and Circular Materials

Meri Cvetkovska[1](✉), Milica Jovanoska-Mitrevska[1], Ana Trombeva Gavriloska[2], Mirjana Laban[3], Suzana Draganic[3], and Marija Jelcic Rukavina[4]

[1] Department of Mechanics and Materials, Faculty of Civil Engineering, Ss Cyril and Methodius University in Skopje, Skopje, North Macedonia
cvetkovska@gf.ukim.edu.mk
[2] Faculty of Architecture, Ss Cyril and Methodius University in Skopje, Skopje, North Macedonia
[3] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia
[4] Department of Materials, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia

Abstract. The transition toward a circular economy in the construction sector promotes the reuse of materials, the development of bio-based composites, and the recycling of industrial waste streams. While these strategies significantly reduce resource consumption and environmental impacts, they also introduce new challenges related to fire safety, material performance, and regulatory compliance. Circular construction increasingly incorporates combustible bio-based materials, recycled polymers, and waste-derived composites, which may alter fire behavior and increase fire loads in buildings. This paper reviews recent developments in circular construction materials, including bio-based composites, recycled tire rubber concrete, wood-based insulation foam, and agricultural waste reinforced polymers. Furthermore, the study discusses the role of bio-based flame retardants, and the emerging regulatory challenges related to hazardous substances and waste reuse. The findings highlight the need for integrated design approaches that combine sustainability, fire safety engineering, and risk management frameworks. Achieving safe circular construction requires collaboration between researchers, industry, and policymakers to ensure that environmental benefits do not compromise building safety.

Keywords: Fire Safety · Combustible Materials · Circular Materials · Recycled Materials · Bio-based Composites · Sustainable Construction

1 Introduction

The construction sector is a major consumer of raw materials and a significant contributor to environmental degradation, accounting for substantial energy use, greenhouse gas emissions, and waste generation across the building lifecycle [1]. In response, circular economy (CE) principles have emerged as a key strategy to improve resource efficiency and reduce environmental impacts in the built environment.

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CE approaches aim to replace the linear "take–make–dispose" model with systems that prioritize reuse, recycling, and extended material lifespans [2]. In construction, this includes design for disassembly, modularity, adaptability, and the use of renewable and recycled materials, reducing construction and demolition waste while improving sustainability performance, [3]. Circular construction increasingly incorporates recycled and waste-derived materials, such as recycled aggregates, rubberized concrete, bio-based composites, and polymer-based products [4]. While these reduce reliance on virgin resources, they often exhibit different mechanical, thermal, and durability characteristics compared to conventional materials.

A key challenge is fire safety. Many bio-based and polymer-based materials are combustible or behave differently under fire exposure, potentially increasing fire loads, flame spread, and smoke production. Reused materials may also lack reliable fire performance data or fail to meet current regulatory requirements. Circular construction systems must therefore ensure adequate structural integrity and fire resistance, including designs intended for disassembly and reuse. Addressing these challenges requires integrating material science, structural engineering and fire safety engineering. Achieving safe and sustainable circular construction depends on balancing environmental benefits with fire performance and structural reliability.

This paper examines the relationship between circular construction materials and fire safety, reviewing recent material developments, evaluating fire and structural performance, and discussing associated regulatory challenges.

2 Circular Materials

The transition toward a circular economy in the construction sector has led to an increased adoption of recycled, reused, and bio-based materials. While these approaches improve resource efficiency and reduce environmental impacts, they also introduce new challenges related to fire safety. In particular, the thermal behaviour, combustibility, and structural performance of circular materials under fire exposure may differ significantly from those of conventional construction materials.

Based on a review of existing literature defining the material characteristics and the thermal response of various circular materials [2–21], a classification framework for circular materials is proposed, focusing on their origin and circularity characteristics. Materials are categorized into four main groups: reused (RU), recycled (RC), renewable (RN), and those providing additional environmental benefits (ECO) (Table 1). This classification is essential for subsequent fire analysis, as it enables systematic evaluation of the fire performance and behaviour of different circular material groups.

Table 1. Classification of circular construction materials.

Material	Reused (RU), Recycled (RC), Renewable (RN) and Additional Environmental (ECO) Benefits
Metals	(RU/RC): steel; aluminum

(*continued*)

Table 1. (*continued*)

Stone and fired clay	(RU): stone; fired clay bricks; (RC): ceramic materials
Timber, bamboo, bio-based materials and composites	(RU/RC/RN/ECO): timber; bamboo; engineered timber/bamboo; cork (RC/RN/ECO): natural fiber-reinforced composites; wood fiber; hemp; flax; kenaf; jute; sisal; coir; bamboo fiber; cellulose; mycelium-based materials (RU/RN/ECO) straw
Concrete, cementitious and lime-based materials	(RU): concrete/mortar; (RC): concrete/mortar with recycled aggregates including mineral-based, glass-based, ceramic-based, polymer-based and bio-based aggregates; (RC/ECO): low-carbon concrete/mortar; (RU/RC/ECO): lime-based concrete/mortar; (RC/ECO): geopolymer concrete/mortar
Glass	(RU/RC): glass; foamed glass
Polymers and polymer fiber-reinforced composites	(RC/RU): plastic structural profiles/lumber; thermoplastic structural composites; reprocessable fibre-reinforced composites; (RU/RC): PET; polyester; some rubber products etc.
Earthen materials	(RU/RN/ECO): rammed earth; adobe; cob; compressed earth blocks
Animal-based materials	(RU/RC/RN/ECO): sheep wool

3 Fire Performance Classification of Materials and Elements

In addition to material origin and circularity, fire performance is a critical parameter in building design and regulation. Fire classification systems distinguish between reaction to fire, describing a material's contribution to fire development (ignitability, flame spread, heat release, and smoke production), and fire resistance, referring to the ability of a building element to maintain structural and functional performance under fire exposure. According to EN 13501-1 [22], construction materials are classified into Euroclasses A1–F based on reaction-to-fire performance:

- A1–A2: non-combustible or limited combustibility
- B–C: combustible with limited contribution
- D–F: highly combustible

Additional classifications address smoke production (s1–s3) and flaming droplets or particles (d0–d2), providing a standardized framework for evaluating and comparing fire behavior.

Fire resistance is defined over a specified period under standard fire exposure or over the full duration of a parametric fire EN 1991-1-2 [23]. It is expressed through:

- R (load-bearing capacity): ability to maintain mechanical resistance
- E (integrity): ability to prevent passage of flames and hot gases
- I (insulation): ability to limit temperature rise on the unexposed side

These criteria are often combined (e.g., REI 60), indicating that an element satisfies load-bearing, integrity, and insulation requirements for 60 min under standard fire exposure, or throughout the fire duration in parametric design.

4 Fire Behavior of Circular Materials

The fire behavior of circular materials depends on composition, prior use, processing history, and system integration. Unlike conventional materials, reused and recycled products may vary in ignitability, heat release, smoke production, and structural performance, requiring assessment at both material and system levels.

In the following sections, the most representative material groups are examined based on a review of the existing literature. Table 2 summarizes the fire behaviour and corresponding fire safety strategies for key circular material groups, classified according to the Euroclass system.

Table 2. Fire safety considerations for circular construction materials

Euroclass	Material Type	Typical Materials	Fire Behavior	Fire Safety Strategy
A1–A2	Mineral-based materials	RCA; recycled brick/masonry; glass (cullet, foam glass); fly ash; GGBS; silica fume; geopolymer concrete; mineral composites	Non-combustible; negligible heat release; no smoke; high thermal stability	Structural optimization; spalling control; mineral binders/additives
B–C	Wood-based composites	Treated timber; engineered wood (e.g., CLT) *(untreated typically D)*	Combustible; forms protective char layer	Fire-retardant coatings; protective linings
B–C	Natural fiber composites (treated)	Hemp; flax; cellulose; cork; bio-based insulation	Pyrolysis; potential char formation	Bio-based flame-retardant systems
D–F	Polymer insulation	EPS; polymer foams; synthetic insulation	Melting/dripping; promotes fire spread	Flame-retardant additives; encapsulation
D–F	Recycled plastics	HDPE; PVC; PET; plastic products	High heat release; rapid ignition; dense/toxic smoke	Material modification; flame retardants; encapsulation

(*continued*)

Table 2. (*continued*)

Euroclass	Material Type	Typical Materials	Fire Behavior	Fire Safety Strategy
E–F	Untreated bio-based materials	Straw; bagasse; husk panels; untreated cellulose; some mycelium materials	Rapid ignition; fast flame spread; high smoke production	Fire-retardant treatment; material modification

Mineral-Based Circular Materials: Mineral-based materials exhibit the most favorable fire performance, remaining non-combustible (Euroclass A1–A2) and not contributing to fire growth. Recycled concrete and reused brick can retain these properties provided it is free from contaminants. Recycled aggregate concrete behaves similarly to conventional concrete; although spalling, strength loss (300–600 °C), and cracking may occur, structural integrity is generally maintained [6, 7].

Recycled additions such as rubber, plastics and industrial by-products influence performance [8–10]. Optimized values of rubber may reduce strength but improve ductility, reducing explosive spalling and limiting heat penetration [8], while pozzolanic additives enhance bonding and reduce porosity [10]. Geopolymer concretes show excellent high-temperature resistance [11].

Bio-Based Materials: Bio-based materials (e.g., timber, cellulose, hemp, straw, wood fiber composites) are inherently combustible and undergo pyrolysis, promoting ignition, flame spread, and smoke production. Bio-composites provide low density and insulation but increase fire load; their performance depends on fibre type, treatment, and matrix compatibility [12]. They ignite readily, contribute to fire growth, and may sustain smouldering [13], although char formation can reduce heat release. Fire-retardant treatments can significantly improve performance, enabling classifications up to Euroclass B–C [24].

Engineered systems, such as cellulose-based composite foams with bio-based flame-retardant systems, demonstrate improved fire resistance, low thermal conductivity (~0.050 W/m·K) and good mechanical properties [14]. Timber exemplifies controlled combustibility, forming a protective char layer that slows degradation and maintains structural capacity, with further improvement through treatments and linings [15]. Bio-based flame retardants derived from lignin, cellulose, and tannins act via char formation, heat absorption, and inert gas release. although challenges remain in compatibility and processing [16].

Polymer-Based Circular Materials: Recycled polymers (plastics, rubber, insulation) present the highest fire risk, characterized by rapid ignition, high heat release, dense smoke and toxic gases, and melting or dripping, all promoting fire growth.

Fire behavior varies due to additives, contaminants, and recycling-induced degradation. Expanded polystyrene (EPS) is inherently combustible but can achieve improved performance when treated or protected [17]. Untreated polymers are typically Euroclass D–F, while treated systems may reach B–C depending on formulation [18].

Due to their high fire contribution, polymer-based materials require strict control through material modification, flame-retardant additives, encapsulation, and system-level fire safety design.

Waste-Derived and Hybrid Composite Materials: combine mineral, bio-based, and polymer components, resulting in variable fire behavior governed by composition and structure. Higher mineral content improves fire performance, while increased polymer or organic fractions increase combustibility [19]. Cementitious systems with recycled materials can achieve improved thermal stability and fire resilience despite some strength loss under fire exposure [19], with certain components also reducing heat penetration. Overall, the fire behavior of hybrid composites cannot be inferred from individual constituents and must be evaluated at the system level.

Material treatments further enhance performance; for example, epoxy composites reinforced with carbonized cow bone particles improve flame resistance through char formation and thermally stable mineral phases, reducing flammability and smoke production [20], whereas untreated organic fillers increase fire load.

5 Waste Management and Circularity Indicators

In addition to in-service performance, fire risks also arise during storage and handling of circular materials and waste. Waste storage and management are critical yet often overlooked in circular construction. Improper handling of construction and demolition waste can lead to contamination, inefficiencies, and increased fire risk, particularly from accumulated combustible materials.

Recent research [21] emphasizes integrating storage and stockpiling into circularity indicators. The Storage Circularity Indicator (SCI), based on fire risk assessment, evaluates hazard likelihood and severity, highlighting the need to consider fire safety across the entire material lifecycle [21].

Circularity indicators also assess reuse efficiency through metrics such as recovery rates, energy consumption, and emissions. However, waste reuse introduces challenges related to contamination and material quality, requiring advanced sorting, quality control, and standardized certification to ensure safe application.

6 Regulatory and Design Challenges

Although circular economy strategies are widely promoted, regulatory frameworks have not yet fully adapted to their implementation. Existing fire safety regulations are largely based on standardized testing methods developed for conventional materials and may not be directly applicable to reused or recycled products.

Reuse introduces significant challenges related to certification, traceability, and quality assurance. Materials may require re-evaluation due to ageing, mechanical damage, environmental exposure, or missing documentation, and are often restricted due to uncertainties in performance [3]. In this context, performance-based fire design provides a valuable alternative, enabling analytical assessment beyond prescriptive testing and supporting the broader adoption of circular materials.

Additional risks arise from hazardous substances in recycled materials, including persistent additives such as plasticizers, stabilizers, flame retardants, and heavy metals. Regulatory fragmentation, particularly between REACH and waste legislation, creates gaps in risk assessment and complicates compliance.

Furthermore, both reused and recycled materials exhibit inherent variability. Reused materials may be affected by prior thermal loading or undocumented treatments. Recycled materials introduce uncertainty due to heterogeneous feedstocks, contamination, and reprocessing. Changes in use conditions add another layer of complexity, as materials are frequently redeployed in new assemblies where system-level interactions govern fire response. A structured verification approach is therefore essential, including traceability, condition assessment, evaluation of existing fire performance data, and, where necessary, supplementary testing or engineering-based assessment.

Effective implementation of circular construction thus requires integrated frameworks that combine material evaluation, exposure assessment, and regulatory compliance. These should be supported by decision-making tools and interdisciplinary collaboration to ensure that circularity objectives are achieved without compromising fire safety.

7 Discussion

Fire behavior of circular materials is governed by composition and structure. Mineral-based materials provide the best performance, while bio-based materials are combustible and require fire-retardant strategies, and polymers present the highest fire risk due to rapid ignition, high heat release, and smoke production.

Circular materials do not inherently compromise fire safety; safe use depends on material selection, fire-retardant treatments, and system-level design. Performance-based fire engineering is therefore essential [24].

Although circular strategies offer environmental benefits, their adoption must balance sustainability with safety and regulation. Advances in flame retardants and engineered composites show that fire performance can be improved without compromising environmental goals.

Regulatory frameworks must evolve through harmonization, improved certification, and interdisciplinary collaboration. Timber and façade systems highlight the need for system-level design.

Safe circular construction ultimately requires a holistic integration of materials, design, regulation, and lifecycle considerations.

These findings highlight that fire safety in circular construction is governed not only by material properties but by system-level design and lifecycle considerations.

8 Conclusions

Circular economy strategies improve resource efficiency but introduce materials with diverse and uncertain fire behaviour, governed by both material composition and system configuration.

Mineral-based materials provide reliable fire performance, whereas bio-based and polymer-based materials are combustible and require targeted fire protection strategies, including fire-retardant treatments and system-level design.

Safe implementation is achievable through appropriate material selection, engineered fire protection, and performance-based fire design. Advances in flame-retardant technologies and composite design demonstrate that fire safety and sustainability can be aligned.

However, adoption is constrained by regulatory challenges related to certification, traceability, and hazardous substances, requiring harmonized frameworks and integrated risk assessment.

Future work should focus on advanced fire-safe materials, standardized testing, and lifecycle-based fire assessment. Achieving circular construction requires balancing sustainability with fire safety and structural reliability.

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Adaptability as a Driver of Lower Environmental Impacts: Insights from a Life Cycle Perspective

Matteo Fasciolo(✉), Monica Lavagna, and Andrea Campioli

Politecnico di Milano, Milan 20133, Italy
matteo.fasciolo@polimi.it

Abstract. Adaptability is increasingly recognised as a fundamental requirement for sustainability and circularity in the built environment, yet its environmental implications remain largely unexplored within standard assessment practices. Contemporary buildings are often conceived as rigid, monofunctional systems, leading to premature obsolescence, extensive refurbishment needs, and demolition–reconstruction cycles that generate environmental burdens. Concepts such as Adaptive Design and Circular Design demonstrate that separating long-life and short-life layers, enabling reversible configurations, and allowing spaces and technical systems to evolve can mitigate these impacts. However, adaptability is rarely addressed as a quantifiable environmental variable despite its relevance. Specifically, key determinants of adaptability, including flexibility, convertibility, expandability, and the temporal hierarchy of building layers, can reduce waste, extend component service life, and decrease the frequency and intensity of invasive interventions, while supporting long-term resource efficiency through their close relationship with circular strategies. This paper presents a critical analysis of the selected existing tools developed to evaluate the adaptability potential of buildings from an environmental perspective. The review highlights that they predominantly adopt qualitative approaches and lack quantitative environmental data. At the same time, Life Cycle Assessment (LCA) of buildings rarely integrates adaptability among the aspects considered in the modelling. These findings highlight that adaptability remains a crucial but still under-assessed dimension of sustainable building design. By identifying the methodological limitations of existing adaptability assessment tools, the study clarifies how adaptive strategies may influence environmental impacts over the building life cycle and outlines future opportunities to integrate adaptability into LCA-based environmental assessment of buildings.

Keywords: Building Adaptability · Adaptive Design · Low Impacts · Life Cycle Assessment · Circular Design

1 Introduction

Contemporary architecture faces a growing demand for adaptable construction solutions in response to the need for more sustainable, circular and resilient buildings capable of accommodating evolving functional requirements over time.

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Consequently, buildings, as a central element of the built environment, are increasingly required to adapt to these changing conditions [1, 2], such as internal, external or building-specific factors [3], including shifts in function [4], socio-economic dynamics [5], population trends, and technological advances [6], which increasingly affect building longevity. This process has been further accelerated by the COVID-19 pandemic, which has significantly influenced the shift in office-space demand due to increased digitalisation and new working cultures. This change has led to a steady increase in office vacancy rates across Europe, which have climbed from 6% to 9.7% in the post-pandemic period. As highlighted by the European Commission, this stock of vacant offices represents an underutilised resource that could potentially be converted to address housing shortages, offering a more climate-friendly and resource-efficient alternative to new construction and urban sprawl [7].

Despite the increasing recognition of adaptability as a strategic design priority, buildings are generally designed and constructed as rigid, static, and monofunctional structures, limiting transformation and often favouring demolition and reconstruction over adaptation [8]. In this context, one of the main challenges for stakeholders is the inability to anticipate the range of possible scenarios, mainly due to the difficulty in predicting short- and long-term variability in relation to the risks and costs of change [9]. In response to these challenges, several tools have been developed to assess how easily a building can be modified during its life cycle, both in the case of new construction and existing buildings, focusing on its capacity to be modified with minimal demolition and material waste [10]. However, these tools are typically based on qualitative criteria and focus primarily on physical, economic, and functional variables, while rarely addressing the environmental implications of adaptability interventions, leaving a significant gap in quantifying the environmental impacts of adaptable solutions over time. This limitation is reflected in the LCA of buildings according to EN 15978:2011 [11], which does not incorporate variables related to the adaptability and transformation capacity of buildings, and LCA studies of buildings rarely incorporate this aspect. This limitation means that the potential environmental benefits of building adaptability remain largely unquantified and insufficiently documented, limiting designers and stakeholders in making decisions based on environmental data.

Institutional recognition confirms the urgency of developing scientifically sound methods to assess and compare adaptability strategies within a life cycle perspective. At the international level, the relevance of adaptability is formally acknowledged in ISO 20887:2020 [12], which explicitly addresses adaptability within a sustainability perspective, while, at the European level, the EU Level(s) framework highlights its relevance through Indicator 2.3 [13], which promotes the design of buildings able to adapt to future changes to reduce environmental impacts from premature demolition and large-scale renovation, while promoting a more comprehensive perspective and encouraging the wider application of LCA.

Against this background, this study investigates how existing adaptability assessment tools address environmental implications and whether they incorporate environmental indicators capable of supporting life cycle-based evaluation approaches.

2 Materials and Methods

The analysis presented in this paper is based on a targeted review of existing tools developed to assess the adaptability potential of buildings. Tool identification was informed by the authors' expertise and further grounded in previous comprehensive reviews conducted by Askar et al. [10] and Mlote et al. [14], which provided an overview of the main methodological approaches developed in this field.

Unlike previous reviews, which mainly examined the conceptual and methodological characteristics of these tools and their capacity to support adaptive design decisions, the present study complements the existing research by analysing these tools from an environmental perspective. Based on these studies, the present work focuses on the most relevant tools operating at the building scale, while tools addressing adaptability at the material or component scale were intentionally excluded.

In particular, the selected tools were analysed according to their objectives, application phase, methodological structure, and their ability to address the potential avoided environmental impacts associated with the implementation of adaptability strategies. In addition, their potential integration into LCA-based assessments was examined in relation to replacement and refurbishment rates, transformation scenarios, disassembly rates, reuse potential, end-of-life streams, and avoided impacts during the reference study period.

3 Results

The analysis of adaptability assessment tools reveals a significant discrepancy between the theoretical recognition of adaptability as fundamental for sustainability and its quantification through environmental metrics. Although previous research [10] identifies adaptability as a critical enabler of circular economy strategies, most of the tools analysed remain within qualitative or purely economic evaluation frameworks, lack validation methods, and do not assess the environmental impacts of implementing adaptable strategies to demonstrate their effectiveness. The following sections analyse the identified tools (Table 1) according to their role within the building process, dividing them into decision-making support tools for existing buildings, design tools for new buildings, and cross-phase tools for new and existing buildings.

3.1 Decision-Support Tools for Existing Buildings

Adaptive Reuse Potential (ARP), 2008. The ARP model [15] is a pioneering framework for ranking existing building stock by their potential for conversion, using physical, economic, functional, technological, social, and legal obsolescence criteria to estimate useful life. Although the model does not include explicit environmental criteria, as one of the earliest systematic contributions in the field, it emphasises the concept of residual value, assuming that extending the use of existing structures can contribute to more sustainable resource management. Although it does not provide a quantitative assessment of environmental impacts, from an LCA perspective, the residual life data could inform reference service life (RSL) assumptions and model realistic adaptive reuse scenarios.

IconCUR, 2012. This model [16] is a conceptual framework that supports property and facilities managers in selecting appropriate management strategies for existing assets, including reconstruction, conservation, renovation, or adaptive reuse (AR). Based on a multi-criteria decision analysis (MCDA), it maps property performance within a three-dimensional space defined by condition, utilisation, and reward. Within this framework, environmental aspects, such as carbon footprint and habitat protection, are included within the reward dimension together with financial, cultural, and community benefits. However, these aspects are assessed through weighted judgement scores rather than through quantitative environmental indicators. By integrating the LCA methodology, these qualitative management assessments could be converted into quantitative environmental weights, enabling a comparative evaluation of different asset management alternatives.

Conversion Potential Assessment Tool, 2018. Also known as the Conversion Meter (CM) [17], this tool evaluates the technical and market feasibility of repurposing vacant office buildings into residential housing through veto criteria for a rapid initial screening and gradual criteria for a detailed classification of an asset's transformation suitability. It focuses on the avoided value loss and the reduced total costs of ownership (TCO), framing life cycle thinking primarily in economic terms. However, it qualitatively frames AR as a strategy to prevent material consumption and "waste of resources" associated with premature demolition. In this regard, CM's technical feasibility criteria can inform the definition of functional transformation scenarios and support assumptions on material retention, replacement needs, and refurbishment intensity within an LCA-based methodology.

3.2 Design-Phase Tools for New Buildings

Adaptable Buildings Design (ABD) Framework, 2010. This framework [18] assesses building adaptability by identifying uncertainties in market demand and technical developments, integrating flexibility options across spatial, structural, and service systems. It applies Real Options Analysis (ROA) and Monte Carlo simulation to show how adaptability can respond to future market and technical changes, although its primary focus remains on financial metrics such as Expected Net Present Value (ENPV). Environmental benefits are considered only indirectly, through extending the building's lifespan and the reduction of the frequency of major interventions and avoiding the waste of resources associated with premature demolition. In addition, the framework aligns with a life cycle planning perspective, simulating how initial construction and subsequent incremental adaptations can be managed to achieve the maximum value of a project. Accordingly, it would be valuable to associate these incremental adaptations with the assessment of avoided environmental impact through reduced renovation cycles, allowing designers to treat adaptability as a strategic reserve for long-term resource efficiency.

AdaptSTAR Model, 2013. This model [19] aims to support adaptability, from the conceptual design stage, through the assessment of the AR potential of future buildings. Through a "star rating" methodology, it evaluates physical, economic, functional, technological, social, legal, and political criteria. Environmental aspects are explicitly included

through criteria such as energy ratings, solar access, and ecological footprint measures. Despite this inclusion, the approach considers lifecycle-related benefits based on best practice design in a qualitative way, lacking the empirical data necessary to measure an asset's actual environmental footprint over time. Therefore, a significant opportunity lies in linking AdaptSTAR's design criteria to predictive material flow models, providing an evidence-based demonstration of how specific strategies, such as Design for Disassembly (DfD), lead to a measurable reduction in material flows and environmental pressure across multiple use cycles.

CIRLAB, 2025. This model [20] is a multi-criteria assessment framework designed specifically for the building sector to bridge the gap between circularity strategies and quantitative environmental performance. Based on Brand's concept of "shearing layers" [21], it assesses four functional building layers, namely Structure, Skin, Space Plan, and Services, considering their different lifetimes and life cycles. Unlike models that consider circularity as a standalone qualitative attribute, CIRLAB uniquely focuses on the environmental dimension, integrating circularity directly with two LCA indicators: Embodied Carbon (EC) and Embodied Energy (EE). This integrated approach ensures that benefits gained from applying circular strategies, such as adaptability or disassembly, are balanced with long-term environmental sustainability, recognising that increased circularity does not automatically lead to a lower environmental impact.

3.3 Cross-Phase Tools for New and Existing Buildings

FLEX 4.0, 2016. This instrument [22], based on the support and infill theory of Habraken [23] and the shearing layers concept by Brand [21], evaluates a building's adaptive capacity across five different life cycle layers: Site, Structure, Skin, Services, and Space Plan. It employs 44 flexibility key performance indicators to measure the ability of the building to respond to changing market demands and user requirements. Although it does not include explicit environmental quantification, its KPI-based structure provides a robust pathway for integration with LCA. Specifically, the adaptability scores for each layer could be used as weighted parameters to refine the estimated service life of components in environmental models. This integration would allow for the translation of qualitative adaptive capacity into measurable environmental outcomes, justifying the environmental value of flexibility in reducing the frequency of major renovation or demolition events.

The SAGA Method, 2019. The Spatial Assessment of Generality and Adaptability (SAGA) [24] method uses graph theory as a mathematical proxy to evaluate the total number of functional organisations a plan layout can support, maximising the functional lifespan of built assets while minimising the need for physical interventions. These spatial data provide a significant starting point, suggesting how geometric versatility can prevent premature building disposal at end-of-life. While this method has been developed with environmental sustainability and waste reduction as primary motivations, the tool does not incorporate explicit ecological indicators within its operational variables.

Table 1. Comparative overview of adaptability assessment tools.

Tool	Application context	Quantitative environmental indicator	Adaptability aspects assessed	Assessment methodology
ARP	Existing building	No	Reuse Potential	Quantitative index
iconCUR	Existing building	Partial	Functional flexibility	Qualitative MCDA
CM	Existing building	No	Conversion feasibility	Semi-quantitative scoring
ABD	New building	No	Spatial/structural flexibility	Real option modelling
AdaptSTAR	New building	No	Adaptive Reuse potential	Weighted checklist
CIRLAB	New building	Yes	Circular adaptability	LCA-based assessment
FLEX 4.0	Both	No	General adaptability	KPI scoring
SAGA	Both	No	Spatial adaptability	Graph-based metrics

4 Discussion

The analysis of existing adaptability assessment tools highlights a clear methodological gap between the recognition of adaptability as a sustainability and circularity strategy and its quantification through environmental indicators. Most of these tools assess *how* to make a building adaptable, including spatial flexibility, functional convertibility and technical modularity, but they rarely demonstrate *how much* these adaptability strategies can effectively reduce environmental impacts over time. In addition, when included, environmental aspects are generally treated using qualitative scores or partial indicators, which are not fully compatible with standardised LCA-based methodologies. Consequently, these tools provide limited support for evaluating the actual environmental benefits of adaptable design strategies or identifying the most effective strategy in terms of whole life cycle impact reduction.

A further methodological challenge concerns the *trade-offs* associated with the implementation of adaptable design strategies. Adaptability may require a higher initial material investment, such as oversized structural elements, redundant service shafts, modular partition systems, or other technical measures, potentially increasing initial embodied carbon emissions [13, 20]. At the same time, these strategies may generate long-term benefits, including fewer invasive interventions, avoiding demolition and reconstruction, the consequent reduction of material waste, and the extension of the service life of building components through easier adaptation to changing functional requirements. An environmental cost-benefit analysis can support the assessment of

the environmental effectiveness of adaptability and circularity strategies, avoiding *burden shifting*. Given this complexity, without a framework that integrates multiple life cycles and post-use scenarios, it is difficult to determine the *break-even point* at which adaptability becomes environmentally preferable to conventional construction.

Operationally, adaptability can be incorporated into LCA not as an additional impact category, but as a set of modelling parameters affecting the timing, frequency and intensity of future interventions (Table 2). In this perspective, layer-based adaptability indicators can inform the RSL of components and the expected recurrence of maintenance, repair, replacement and refurbishment processes, corresponding to modules B2–B5. These assumptions can also be combined with convertibility and spatial flexibility to define alternative transformation scenarios over the reference study period, such as conventional refurbishment, adaptive reconfiguration, or demolition and reconstruction. In parallel, reversibility and design-for-disassembly criteria can support the definition of disassembly losses, reuse rates, residual service life and end-of-life flows, affecting modules B5, C1–C4 and, where appropriate, module D. Finally, the additional material investment required by adaptive strategies should be modelled in A1–A5 and compared with the avoided or reduced impacts generated during later transformation cycles. This would allow the identification of break-even conditions under which adaptability becomes environmentally preferable to conventional design.

Table 2. Potential integration of adaptability tools within an LCA-based methodology.

Tool	Key Modelling Parameter	Modules	LCA modelling implication
ARP/iconCUR	Reference Service Life	B4, B5	Replacement and refurbishment timing
CM/SAGA	Transformation scenario	B5, C1-C4, D	Reuse, adaptation, or demolition scenarios
ABD	Future adaptation uncertainty	B2-B5	Timing of future intervention events
AdaptSTAR	Disassembly/reuse potential	C3, C4, D	End-of-life material flow assumptions
CIRLAB/FLEX 4.0	Layer-based service life	A1-A5, B4, B5	Layer-specific replacement/refurbishment cycles

5 Conclusion and Future Developments

The analysis of existing adaptability assessment tools highlights that adaptability remains an under-quantified but potentially crucial driver of environmental sustainability in the built environment. While current assessment approaches effectively identify the characteristics that enable adaptable buildings, they rarely quantify the environmental implications associated with these strategies over the building life cycle.

The findings highlight the need to move beyond qualitative adaptability assessments towards methodologies capable of translating adaptive capacity into measurable environmental indicators. In particular, integrating adaptability parameters within the LCA methodology would enable the evaluation of avoided environmental impacts associated with extended building lifetimes and improved resource efficiency. Among the analysed tools, CIRLAB [20] represents a crucial advancement, as it integrates circular strategies with quantitative environmental metrics such as Embodied Carbon (EC) and Embodied Energy (EE). The model demonstrates that it is possible to transform adaptability from a theoretical concept to a measurable variable, although its integration within life cycle–based methodology remains partial.

In this perspective, adaptability should no longer be considered exclusively as a design attribute but as a quantifiable parameter capable of supporting environmentally informed decision-making and contributing to the transition towards a more circular, resilient and resource-efficient built environment. Future research should therefore focus on developing operational approaches capable of linking adaptability indicators with life cycle-based environmental metrics, enabling the systematic evaluation of adaptability strategies within building sustainability assessment frameworks.

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Environmental Performance of Adaptive Reuse in Academic Building Conversion – A Swedish Case Study

Md Parvaz[1(✉)], Allan Hawas[1], Shaheda T. Akter[1], Dennis Lindblom[2], Magnus Österbring[2], and Yahya Jani[1]

[1] Department of Engineering Sciences, Mälardalen University, 721 23 Västerås, Sweden
omor.faruk.monsi.parvaz@mdu.se
[2] NCC AB, 170 80 Solna, Sweden

Abstract. The European Union's (EU) climate neutrality targets and renovation-focused policy initiatives highlight the urgent need to reduce embodied carbon in the existing building stock. While circular renovation strategies applied in adaptive reuse projects are increasingly promoted, limited quantitative evidence demonstrates their performance under regulation-aligned assessment frameworks. This study addresses this gap by providing empirical evidence from a major adaptive reuse project in Sweden, involving the conversion of an academic building to office facilities. To evaluate the environmental performance of renovation strategies, two scenarios were defined: a linear scenario assuming full material replacement and a circular scenario incorporating reuse, upgrading, and selective new procurement of building components. Embodied carbon impacts were assessed using two parallel approaches: Sweden's national climate declaration-based model and a product-specific Environmental Product Declaration (EPD)-based model. Both assessments were conducted within life-cycle modules A1–A5, representing material production and construction stages, under identical system boundaries. Results show that the circular renovation scenario reduced embodied carbon by 31% using the climate declaration model and by 39% using EPD-based model. Interior components demonstrated greater reuse potential, while envelope elements were more constrained by technical and regulatory performance requirements. By delivering regulation-aligned, building-scale quantitative evidence, the study positions major renovation as a significant decarbonization pathway. The structured assessment methodology presented in this study can support future renovation projects and policy frameworks aiming to integrate embodied carbon reduction into building regulations and climate strategies.

Keywords: Circular construction · Building renovation · Adaptive reuse · Embodied carbon · Climate declaration · Environmental product declaration (EPD)

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1 Introduction

Buildings account for more than 30% of the EU's environmental footprint, approximately one-third of material consumption, 42% of energy use, and 35% of greenhouse gas (GHG) emissions [1]. In response to the climate crisis, the EU has committed to achieving climate neutrality by 2050 [2], while Sweden has adopted a legally binding net-zero GHG target for 2045 [3]. Achieving these goals requires decarbonizing the existing building stock as almost half of Europe's buildings are over 50 years old and energy inefficient. To support this, the EU's Renovation Wave promotes accelerated and deep renovation of old buildings to meet climate objectives [4].

Adaptive reuse refers to the process of repurposing existing buildings for new functions while preserving much of their original structure and materials. It is increasingly recognized as an alternative to conventional linear renovation [5, 6]. While linear construction typically follows a sequence of extraction, production, use, and disposal, adaptive reuse emphasizes circular strategies. In this context, circular renovation prioritizes the retention, upgrading, and reuse of existing building components, along with the integration of recycled materials, thereby reducing the demand for new resource production [7]. Because material manufacturing typically dominates embodied carbon emissions, circular renovation is widely regarded as a key mitigation pathway [6, 8]. Empirical studies show that retaining structural systems can substantially reduce embodied carbon compared to demolition and new construction [5, 6, 8]. However, recent systematic reviews show that most of the circular construction research focuses on isolated material strategies and recycling technologies, while holistic building-scale renovation assessments remain limited [7, 9]. Furthermore, embodied carbon results are sensitive to data source selection, with documented differences between generic database factors and product-specific EPDs [10, 11].

Despite growing research and policy attention, limited quantified evidence demonstrates how major renovation projects contribute to decarbonization under existing regulatory assessment frameworks. In Sweden, climate declaration requirements apply to new buildings, while substantial renovations are not yet systematically included [12]. This creates a gap between climate policy ambition and measurable implementation. This study aims to provide regulation-aligned empirical evidence from a major adaptive reuse project by comparing linear and circular renovation scenarios using both standardized climate declaration factors and product-specific EPD data. By providing quantified, building-scale evidence, this study demonstrates how embodied carbon reductions from renovation can support Swedish and EU climate neutrality pathways.

1.1 Case Study

The case study concerns the southern academic building at Mälardalen University, known as the S-Building, situated in Västerås, Sweden. The three-storey building was constructed in 1994, with a total gross floor area of 6,778 m^2. In 2024, a major renovation was initiated, scheduled for completion in 2026. Rather than pursuing a conventional renovation approach, the project employed an adaptive reuse strategy, converting the academic building into office facilities. The conversion required significant spatial and

functional reconfiguration. The original classroom-based layout was adapted to accommodate office functions, resulting in internal modifications and selective upgrading of building components to meet contemporary technical and performance requirements.

The renovation was undertaken with high environmental ambition. The project aimed to achieve a 25% reduction in embodied carbon compared to a conventional baseline scenario and to obtain highest grade (gold) under Miljöbyggnad Ombyggnad, a Swedish environmental certification system [13]. The certification framework includes requirements for circular material flows, including thresholds for preservation, reuse, and recycled content in newly added materials. To guide implementation, the project followed a four-step material strategy: preservation of existing elements, upgrading of retained components, internal reuse, and introduction of new products with recycled or low-impact materials only where necessary. This implementation context forms the basis for the methodological approach described in the following section.

2 Methodology

The overall research design is illustrated in Fig. 1. The study follows a structured quantitative workflow comprising data collection, material inventory development, climate impact modelling, and scenario-based comparison. Two parallel calculation approaches: (i) Swedish national climate declaration model and (ii) Specific EPD-based model, were applied to assess embodied carbon performance. The final stage compares a linear renovation baseline with a circular renovation scenario to quantify potential climate savings expressed as total Global Warming Potential (GWP).

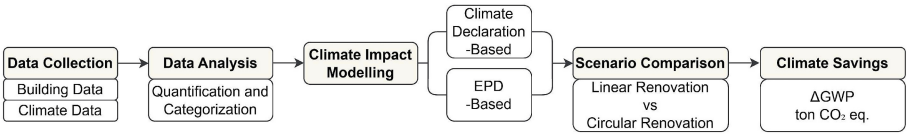


Fig. 1. Research design and quantitative workflow for embodied carbon assessment.

The scope of the analysis is defined by building components affected by adaptive reuse intervention. Figure 2 shows an exemplary section of the adaptation of existing facilities. The conversion from classrooms to office use required substantial spatial and functional reconfiguration, resulting in internal modifications and selective upgrading of building elements. Internal partitions and doors were dismantled to accommodate new layouts, while selected external components, including windows and glass façade elements, were replaced to meet updated technical, fire safety, acoustic, and energy performance requirements. The assessment includes primary construction materials directly influenced by these spatial and technical adjustments. To represent material flows, building components were classified into four categories: (i) preserved components retained without modification, (ii) dismantled components for spatial reconfiguration or technical non-compliance, (iii) upgraded and reused components after necessary interventions (e.g., surface treatment and window glazing replacement while preserving frames), and

(iv) new materials installed to fulfil functional and regulatory requirements. Building data was derived from existing and updated architectural and construction drawings, together with documentation of new materials including technical specifications and product information. Material quantities were extracted from the drawings and compiled into a structured inventory using consistent measurement units.

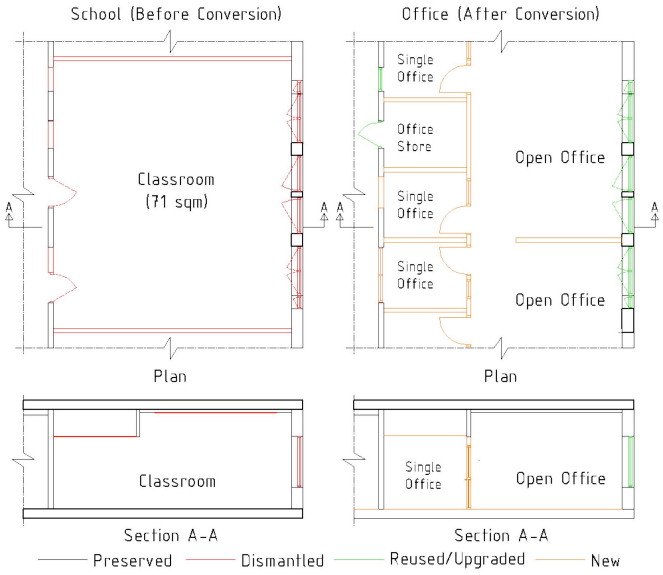


Fig. 2. Conversion of internal layout from academic to office facilities with material flow.

Climate impact modelling was conducted using two parallel approaches. The first model followed the Swedish climate declaration methodology and applied emission factors from the national climate database, supplemented where necessary by the Finnish SYKE database [14, 15]. The second model applied product-specific EPD data for new materials, reflecting manufacturer-specific environmental performance. A total of 17 purchased product-specific EPDs were used, all third-party verified, valid at the time of assessment, and issued under recognized program operators. Both models used the same quantified material inventory to ensure scenario comparability. Sources were documented material-by-material to ensure transparency and reproducibility. During the calculations, factors were normalized per component area (m^2) using appropriate conversion factors, enabling aggregation of embodied carbon at building level, expressed as total GWP (ton CO_2 eq.).

The system boundary for embodied carbon assessment was defined in accordance with EN 15978:2011 [16]. For new materials, the assessment included production and construction stages (A1–A5). For reused or upgraded components, the deconstruction stage (C1) associated with dismantling was included, together with A1–A5 for materials requiring upgrading or partial replacement. Within this boundary, the linear renovation scenario assumes complete replacement of dismantled and upgraded components with newly manufactured materials fulfilling the same technical and functional requirements,

without reuse or material recovery. In contrast, the circular renovation scenario incorporates reused and upgraded components supplemented by selective new procurement. Preserved components retained in situ were excluded from both scenarios, as no additional production or construction processes were associated with them. Climate savings were calculated as the difference in total GWP between the linear renovation baseline and the circular renovation scenario.

3 Results and Discussion

The results present the quantified material flows and associated climate impacts of the renovation, providing the basis for evaluating the effectiveness of circular strategies implemented in the project. Table 1 presents the material inventory of the circular renovation, categorized as preserved, dismantled, reused/upgraded, and new materials.

Table 1. Material inventory categorized by intervention type, expressed in m^2.

	Component	Material	Preserved	Dismantled	Reused/Upgraded	New
External	Window	Wooden	0	946	887	59
	Glass Façade	Wooden	0	410	0	410
	Door	Steel	30	33	0	33
Internal	Flooring	Textile	0	0	0	3101
		Ceramic	39	0	0	48
		Vinyl	29	0	0	36
		Linoleum	1508	0	0	810
	Ceiling	Gypsum Panel	3701	2939	2710	386
	Partition & Door	Wooden Door	69	167	79	92
		Steel Door	17	8	0	8
		Glass Partition	391	283	209	285
		Gypsum Panel	5590	5077	1751	3240

Figure 3 illustrates the proportional distribution across component groups. The results reveal a clear distinction between internally driven spatial transformation and externally driven technical upgrading. Internal modifications were primarily motivated by the conversion from classroom layout to office configuration, requiring reorganization of partitions, doors, and ceilings. Despite this spatial restructuring, internal systems retained substantial circular potential: ceilings achieved 54% preservation and 40%

reuse/upgrading, while internal partitions and doors retained 52% of material with an additional 17% upgraded. Flooring systems showed lower reuse feasibility, with 72% being replaced due to aesthetic and acoustic performance requirements associated with office standards.

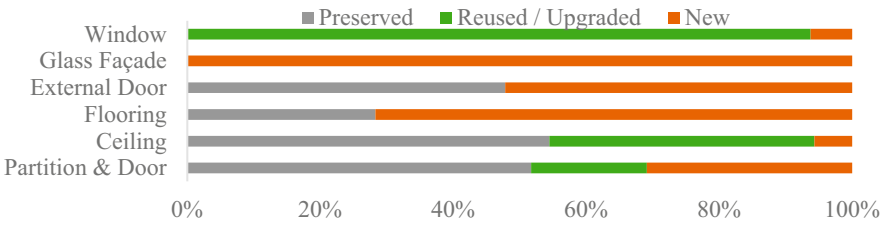


Fig. 3. Percentage distribution of implemented circularity by material quantity (m^2).

External components, by contrast, were governed primarily by technical and regulatory performance thresholds, including acoustic requirements, durability, and operational energy efficiency. Window systems demonstrated this dynamic: although 94% of the window area was upgraded and reused, glazing performance was improved from double to triple pane to meet energy standards. The glass façade exhibited no reuse potential and was fully replaced to comply with updated acoustic requirements, as mentioned in the project documents. The comparison indicates that circular feasibility is more strongly constrained by technical performance requirements than by spatial reconfiguration. Interior layout changes do not necessarily prevent material reuse, as many internal components can be preserved, relocated, or upgraded during renovation. In contrast, external components are more constrained by technical performance requirements such as energy efficiency, durability, and acoustic standards. However, reuse feasibility remains case-specific and depends on the objectives of the building adaptation. Different conversion goals can require different technical upgrades that affect how much material can be reused. The combined climate impact results are presented in Fig. 4. Under the climate declaration model, total embodied carbon amounted to 302 ton CO_2 eq. for the linear renovation scenario and 208 ton CO_2 eq. for the circular renovation scenario, corresponding to a reduction of 31%. Under the EPD-based model, emissions were 161 ton CO_2 eq. for linear renovation and 98 ton CO_2 eq. for circular renovation, yielding a reduction of 39%.

These results demonstrate that implemented circular strategies, combined with selective upgrading and targeted material replacement, can substantially reduce embodied carbon in renovation projects. This finding is consistent with previous building-scale adaptive reuse assessments. Gursel et al. [6] reported reductions of 34–48% when comparing adaptive reuse with new construction, while other case studies similarly show that retaining existing structural systems and materials significantly lowers embodied carbon impacts [5]. Although the scope of the renovation varies across studies, these findings confirm that circular strategies can deliver substantial climate benefits. The two calculation approaches provide important methodological and regulatory insight. The climate declaration model reflects standardized national emission factors, ensuring comparability across projects, whereas the EPD model captures product specific environmental

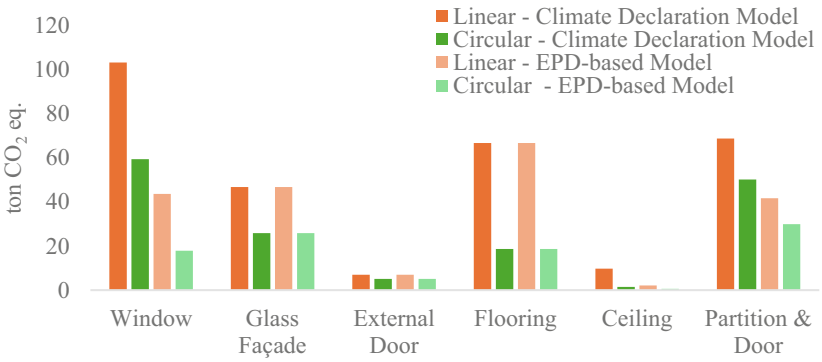


Fig. 4. Embodied carbon comparison between linear and circular renovation scenarios.

performance. The lower embodied carbon obtained in the EPD model primarily results from the use of manufacturer specific data for products with optimized production processes, recycled content, and lower carbon material compositions. In contrast, the climate declaration database applies conservative generic values intended for regulatory comparability. Consequently, the EPD model captures procurement driven climate reductions that are not fully visible in standardized datasets. This highlights that strategic material selection plays a crucial role in maximizing climate savings. Furthermore, the results expose a regulatory gap. Current Swedish climate declaration requirements apply to new buildings, while major renovation projects are not formally included yet. Given the scale of the old building stock across Europe and indicated 31% climate savings, systematic integration of circular renovation into national climate declaration frameworks could contribute meaningfully to achieving long-term climate neutrality targets. Supporting this statement, Sweden is planning to bring major renovation projects under climate declaration from 2027 [17].

4 Conclusion

This study provides empirical, implementation-based evidence on the embodied carbon implications of circular strategies in a building adaptation project. By quantifying material flows and assessed climate performance under Swedish climate declaration model and specific EPD-based model, the results demonstrate that circular renovation can reduce embodied carbon by 31% and 39%, respectively, compared to conventional linear renovation. These reductions were achieved through preservation, reuse, upgrading, and selective replacement combined with strategic low-carbon material procurement. The findings highlight the significant potential of major renovation projects, which can deliver substantial embodied carbon reductions through circular material strategies. Despite this potential, such projects are not yet systematically included in national climate declaration frameworks. Integrating major renovation into these frameworks could improve embodied carbon transparency and support progress toward Swedish and EU climate neutrality targets. However, the study is subject to several limitations, including climate data

availability, estimation of material quantities from construction drawings, and restriction to life cycle modules A1–A5. The transferability of the quantified climate savings depends on project-specific factors such as functional & technical requirements, regulatory constraints, level of renovation and availability of reusable components, although the methodological framework itself could be applicable to other renovation contexts. Future research should integrate comprehensive life cycle cost and environmental assessments to evaluate economic–environmental trade-offs and to support evidence-based development of renovation-focused climate policies.

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Reuse and Recycle of Materials in Construction: A Case Study of Circular Design

Dimitrios Karadimas[1(✉)], Eleni Latsi[2], Petros Mainas[2], and Marios-Zois Bezas[2]

[1] School of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece
dkaradic@civil.auth.gr

[2] Department of Civil Engineering, University of West Attica, Athens Egaleo 12241, Greece

Abstract. Reusing and recycling in construction reduce the need for new raw resources, minimize greenhouse gas emissions and decrease material waste. Studies show that reclaimed concrete elements can reduce CO_2, equivalent emissions by up to 75% compared with new concrete construction and can lower upfront greenhouse gas emissions by about 80% in floor system designs. Following the principles of reuse, recycling, and sustainable structural design, a case study of a student dormitory is presented in the paper. The process of circular design and selecting final solutions for the global environment is shown to be a feasible target.

More specifically, the dormitory is constructed by materials taken from a disassembled old industrial building. The new facilities consist of four buildings, two of which are constructed from structural steel and two of reinforced concrete, aiming to optimize the available materials. Through this case study, a reuse/recycling rate of up to 49% has been achieved, while the benefits in terms of cost efficiency and material savings are clearly demonstrated.

Keywords: Circular Design · Reuse and recycle · Disassembly · Case Study

1 Introduction

The infrastructure sector remains one of the largest consumers of raw materials and a major contributor to construction and demolition waste, highlighting the urgent need for circular design strategies and systematic reuse of building materials in architectural design and urban development. In this context, the industry must adopt more sustainable practices capable of reducing its carbon footprint and supporting the transition towards a circular economy. One approach is the application of the 3Rs waste management hierarchy (Reduce–Reuse–Recycle) in structural engineering, which can promote innovative design approaches and structural systems that minimize environmental impacts while improving material efficiency [1–4].

In recent years, significant efforts have been made in Europe and worldwide to establish design rules and recommendations for the recycling and reuse of materials in construction. The Waste Framework Directive 2008/98/EC [5] defines the waste hierarchy, prioritizing prevention, reuse, and recycling, and sets a target requiring that at least 70% of non-hazardous construction and demolition waste be recovered. For concrete

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structures, EN 206 [6] and EN 12620 [7] permit the use of recycled aggregates under specific quality requirements, while in steel construction, EN 1993–1 [8] and CEN/TS 1090–201 [9] provide guidance for the design and assessment of reused structural steel components. These regulations and standards collectively support the safe integration of recycled materials and reused structural elements in construction, while maintaining structural reliability and environmental performance.

Within this framework, the present study investigates how circular design strategies and reusing of construction materials can be incorporated into the development of student housing. The design proposal responds to the increasing demand for student accommodation in large metropolitan areas and explores the role of reclaimed materials in contemporary architectural design. In the examined scenario, an existing industrial building is assumed to be disassembled, allowing its structural steel components and concrete aggregates to be reused in the new construction.

This case study highlights the benefits of material reuse in terms of environmental performance and cost efficiency, while contributing to the broader discussion on circular construction practices, adaptive reuse, and sustainable campus development.

This project was carried out in the context of the national student competition "ecoDomus 2025", organized by Democritus University of Thrace.

2 Reusable Materials

As mentioned in Sect. 1, in the present case study an old industrial building is dismantled, and its materials and structural components are subsequently reused for the construction of a new infrastructure. Table 1 summarizes the available quantities of the materials that can be reused.

Table 1. Available Materials for Reuse.

Materials	Quantities	Cross-sections
Concrete	1,322.14 m^3	–
Steel members	2,210 pieces	HEA180, IPE120, SHS70x5, SHS90x5 & SHS100x5
Steel panels	1,010 pieces	–
Glasses	85 pieces	1.5 m × 3.0 m
Ceramics	5,54.72 m^3	–

The reuse of structural steel elements presents significant environmental benefits, as it reduces the need for both new extraction activities and production of primary raw materials [4]. The process of dismantling the existing metal components rends them easily adaptable to the requirements of the new construction; modification of bolted holes, cutting of sections or welding them facilitate their compliance with the required dimensional and structural specifications of the new structure. In addition, if large spans are required, the recommendations of Ref. [10] may be applied to design the connections between the elements.

Although concrete cannot be reused in its original form in the new structure – except in the case of prefabricated concrete panels – its aggregates can be reused if they meet specific technical requirements. The reuse of existing aggregates significantly reduces construction waste and supports the objectives of the European Green Deal, while also aligning with the principles of sustainable financing in the construction sector [11]. In addition to the reuse of primary construction materials, further benefits in terms of cost reduction and waste minimization can be achieved through the reuse and recycling of secondary materials, such as glass and ceramics. Pollutant emissions from glass recycling are relatively lower than those from steel and concrete, saving up to 30% of energy compared to the production of primary glass, thereby enhancing the environmental efficiency of construction projects. The reuse of the glass panels is permitted when they comply with the requirements of the new project, while ceramic materials can be reused after processing to remove adhered residues of concrete, mortars, and roughcasts, which prevent their direct use. However, according to EN 12620, the fragments can be used as recycled aggregates in low-demand applications [7].

Obviously, material and components that cannot be directly integrated into the new structure can be either recycled or sold, allowing the generated revenue to offset the procurement cost of additional materials.

The implementation of the above practice can be supported by the "material passport" methodology, which involves the systematic documentation of the origin, technical characteristics, and suitability of reusable construction materials. In addition to improving traceability, this approach facilitates the structural assessment and certification process of reclaimed elements through the availability of documented inspection, testing, and maintenance records. Consequently, the reliability and compliance of reused materials with current structural safety requirements and Eurocode provisions [5–11] can be more effectively evaluated before their reintegration into new construction projects. This methodology therefore strengthens both the application of circular economy principles and the safe reuse of structural components in the construction sector [12].

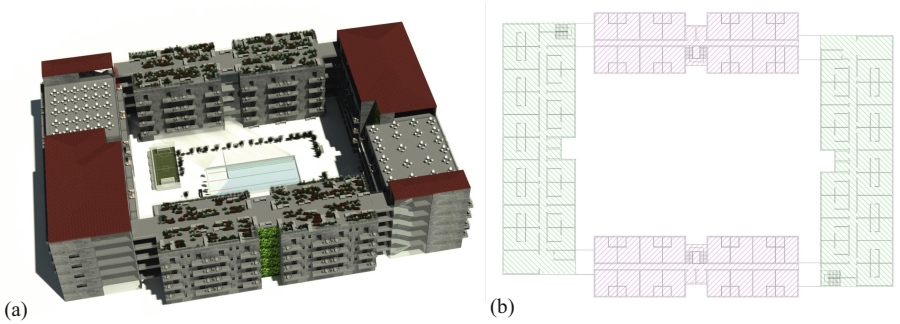
3 Description of the Case Study

3.1 Architectural and Functional Details

A 3D view of the studied residential complex (dormitories) is illustrated in Fig. 1a. The proposed complex includes single- and double-occupancy rooms, as well as fully accessible accommodation units for people with disabilities (PwD), responding to the growing demand for student housing. The architectural composition is organized into four distinct four-story wings that are interconnected through short-span bridges; two constructed of reinforced concrete and two of structural steel and concrete slabs, as distinguished in Fig. 1b. The reason for using different materials in the various substructures aims of using all the available resources resulting from the disassembly of the industrial building, which prevents the development of four structures of the same structural system. The concrete wings have dimensions of 44.40 m × 13.20 m × 16.50 m, while the steel ones measure 54.37 m × 15.80 m × 19.50 m.

In the steel-framed building, a repetitive spatial configuration is applied across the first four floors. Each floor comprises 8 single residential units designed for people with

disabilities (PwD), each with a floor area of 28.32 m^2 and a private balcony of 7.5 m^2. Additionally, 10 double residential units of 36.48 m^2 are provided per floor, also featuring private balconies of 7.5 m^2 and an ergonomic layout designed to comfortably accommodate two students. The reinforced concrete building consists of 15 single residential units per floor across the first four levels. Each unit provides a net floor area of 26.92 m^2 and includes a private balcony of 5.85 m^2, offering a functional and comfortable living environment.



(a) (b)

Fig. 1. (a) Perspective view of the dormitories, (b) Floor plan view where reinforced concrete is in purple and composite in green.

The independent housing units lack integrated kitchens, with shared cooking and dining areas promoting collective use of infrastructure and reducing resource consumption. In addition, the development provides shared facilities supporting academic and social activities, including a dining area, reading room, gymnasium, multi-purpose hall, student association spaces, communal recreational areas, a commercial space for lease, and supporting technical and operational facilities. Furthermore, and in line to the sustainability principles, the project incorporates an accessible green roof, a glazing system with movable shading louvers, photovoltaic panels and solar water heaters, and high-efficiency appliances to improve overall energy management.

3.2 Site and Urban Context

The proposed complex is planned to be located within the Ancient Olive Grove Campus of the University of West Attica, in the Municipality of Egaleo, Western Attica. The available site covers approximately 100,000 m^2 with a floor area ratio (FAR) of 0.5, allowing the development of student housing in close proximity to the university's educational facilities. The spatial configuration of the site and its relationship with the surrounding campus infrastructure are shown in Fig. 2a and b. This arrangement enhances the functional integration between student accommodation and academic facilities, supporting the creation of a cohesive campus environment.

The intervention follows international brownfield redevelopment practices, transforming underutilized areas into active urban environments that combine educational, residential, and cultural functions. Comparable examples include the EUREF Campus

in Berlin and the NDSM Wharf in Amsterdam. In addition, the proposal aligns with contemporary sustainable planning principles and the concept of the "15-min city", which promotes accessibility, mixed land uses, and reduced dependence on long-distance commuting. Any tree removed from the site during development will be carefully transplanted elsewhere in the project area or in a nearby designated green space to ensure its preservation.

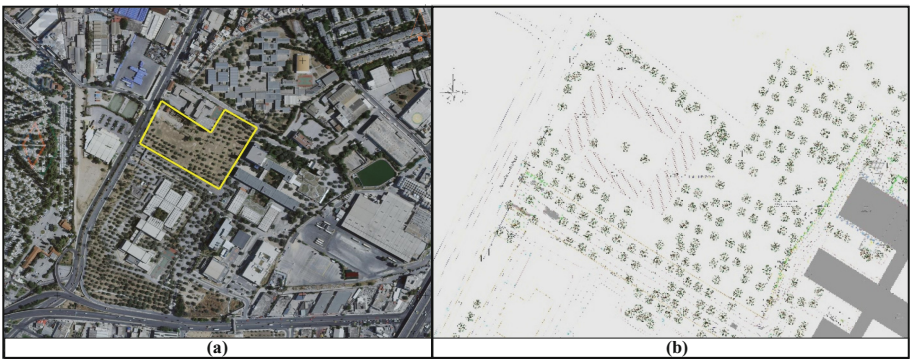


Fig. 2. (a) Extract from the topographic plan of the Ancient Olive Grove Campus of the University of West Attica, (b) Plan view of the infrastructure and existing vegetation.

3.3 Structural Design

This study presents a preliminary design of the sub-structures considering permanent and variable loads, as well as wind and seismic actions. The design of reinforced concrete elements is carried out according to EN 1992-1-1 [13], while steel structural elements are designed following the provisions of EN 1993-1-1 [8]. The aim of this predesign is to ensure the adequacy of the materials available for reuse, estimate the additional materials that need to be procured, and provide an initial cost assessment. To demonstrate the benefits of the circular design, the methodology establishes a comparative framework between two distinct scenarios: a baseline Conventional Scenario (100% new materials) and the proposed Circular Scenario.

3.4 Reuse of Construction Materials

The distribution of the available recycled concrete is intending first to comply with the 30% limit prescribed by EN 206, according to which only this proportion of the concrete in the new structure may consist of reused material. Therefore, a total volume of 772.73 m^3 is allocated in the two reinforced concrete structures (representing the 30% of the concrete in the two new structures and the 58% of the available reusable concrete, see Fig. 3), while 383.51 m^3 is used for the slabs of the composite structures. The remaining quantity of 160.23 m^3, which cannot be directly incorporated in the structural

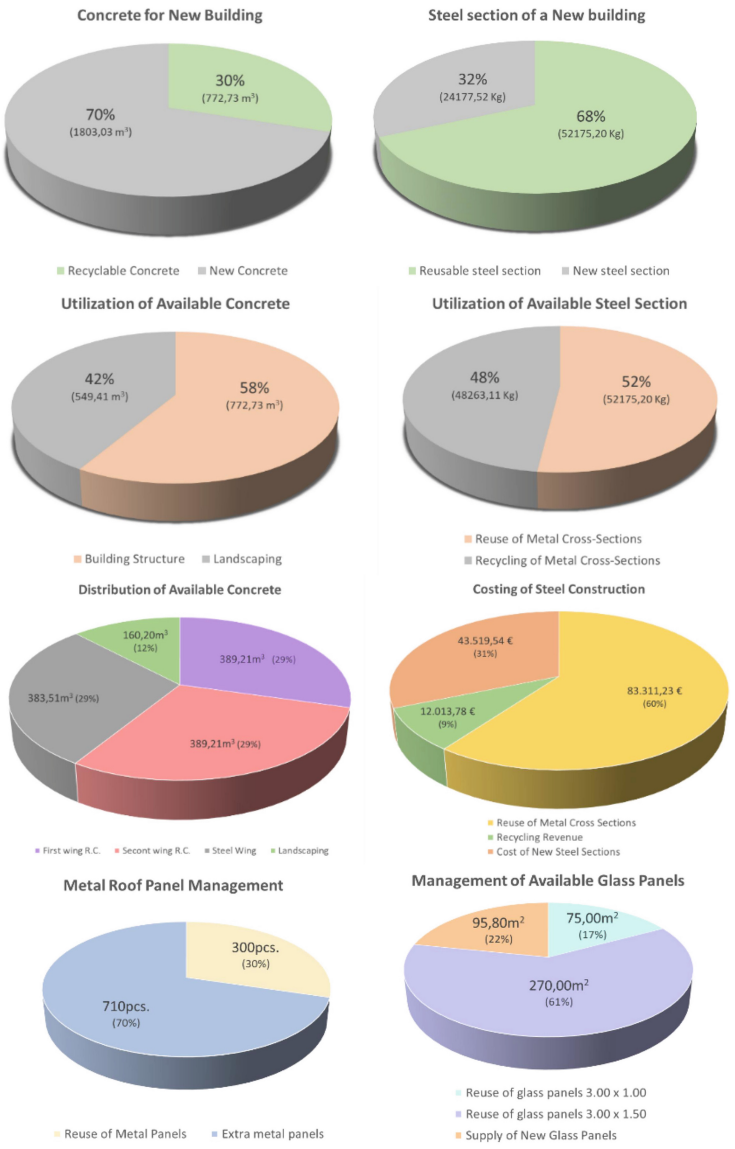


Fig. 3. Distribution of new and recycled materials.

frames, is intended for complementary and secondary construction applications, thereby contributing to the most efficient use of the available resources and eliminating waste.

The total weight of steel required for the steel-framed building is approximately 77,135.86 kg. From the recycling of the existing industrial building, a total of 102,489.51 kg of steel sections was reclaimed, of which 52,175.20 kg – representing 68% of the total required steel and 52% of the available one – are suitable for reuse within the new construction, based on the project's architectural and structural requirements

(HEA 180, IPE 120, SHS 100 × 5, SHS 120 × 5, SHS 90 × 5). To offset the procurement cost of the additional steel sections required (i.e. 48% of the available material, see Fig. 3), it is proposed that the economic value of the surplus and non-reusable sections be realizes through their sale. This is also clearly quantified in Fig. 3, where 60% of the total cost for the steel-framed building is covered by reusing existing components, while from the remaining 40%, a gain of almost 10% is achieved through the recycling of waste material.

It can be seen from Fig. 3, all available metal and glass panels have been reused in the new construction, representing 30% of the total metal panels and 78% of the total glass panels of the new infrastructure, respectively. This further enhances resource efficiency while simultaneously minimize environmental impacts and costs.

Table 2. CO_2 emission per unit, according to EU generic factors.

Materials	Units		Factors [$kgCO_2^e$/un]	Emission [tons CO_2^e]	Percent [%]
Concrete [m^3]	Recyclable	772,73	260,00	200,91	62,86
	New	1.803,30	300,00	540,99	
Steel [kg]	Reusable	52175,20	1,61	84,00	52,99
	Recyclable	48.263,11	0,82	39,58	
	New	24.177,52	1,64	39,65	
Glass [m^2]	Reusable	345,00	13,56	4,68	61,73
	New	95,80	18,69	1,79	

Additionally, a preliminary calculation of the CO_2 emissions has been performed and summarized in Table 2, where material quantities are multiplied by their respective emission factors obtained through Ref. [14]. This assessment highlights that the total carbon footprint is heavily driven by absolute material masses rather than individual coefficients alone. Consequently, since new concrete quantities are more than double of the reused one, concrete emissions inevitably dominate the overall structural footprint, vastly outweighing the contributions of structural steel and glass panels. The last column of Table 2 demonstrates also the percentage reduction in CO_2 emissions achieved by using recyclable materials instead of new ones.

4 Conclusions

The paper investigates the reuse and recycle of materials in construction and demonstrated the benefits of circular design through a case study. More precisely, the design of a student dormitory is presenting, aiming to utilize all available materials resulting from the disassembly of a former industrial building. The study shows that integrating recycled construction materials within sustainable design strategies can improve environmental performance while supporting economic and urban regeneration goals. The design of the studied structure reveals that:

- the use of recycled materials combine with energy-efficient systems and renewable technologies can improve both structural performance and energy efficiency;
- reusing existing materials minimize the need for new raw material and lead to lower energy consumption and fewer air pollutant emissions;
- proper design and management of the materials in the infrastructures could lead to complete elimination of construction waste (100% of available concrete was reused and 52% of the available steel members);
- secondary materials such as glass panels and ceramics could also bring benefits to the circular design process;
- considerable financial gains can be claimed for the new structure.

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A Review of Durability and Resilience in Relation to Structural and Energy Performance

Tania Revnic[1,2(✉)], Ligia Moga[1,2], and Andra Raluca Boroș[1,2]

[1] Technical University of Cluj-Napoca, 25 Baritiu Str., Cluj-Napoca, CJ 400020, Romania
tania.revnic@campus.utcluj.ro

[2] European University of Technology, European Union, Cluj-Napoca, Romania

Abstract. Durability and resilience have become central themes in current discussions on the modernization and long-term performance of the built environment. Although both are essential to more sustainable and circular construction, they have evolved through distinct scientific pathways and continue to reflect different priorities in the assessment of building performance. Durability is generally associated with the long-term preservation of material properties, structural capacity, and energy-related performance under normal operating conditions, as reflected in frameworks such as ISO 15392, EN 15978, and national energy assessment methodologies. Resilience, by contrast, introduces a dynamic and hazard-oriented perspective, referring to the capacity of buildings to withstand, absorb, adapt to, and recover from disturbances such as earthquakes, floods, heatwaves, or energy disruptions, as reflected in performance-based seismic engineering and risk-informed design approaches. This paper presents a critical review of how durability and resilience have been defined, interpreted, and operationalized in relation to structural and energy performance. The analysis highlights the fragmentation of durability-related research, often addressed through separate energetic, environmental, or lifecycle perspectives, while resilience research has developed more strongly in connection with structural safety, climate adaptation, and recoverability. Despite their different origins, the review identifies important complementarities between the two concepts and argues that their integration is necessary for a more coherent whole-life approach to building performance. The paper also outlines emerging directions involving composite performance metrics, multicriteria assessment, and data-informed methods, which may support renovation strategies that jointly address energy efficiency, structural robustness, and climate adaptation in the existing building stock.

Keywords: durability · resilience · structural performance · energy performance · lifecycle performance

1 Introduction

The transition toward a low-carbon and resource-efficient built environment requires more integrated approaches to building performance assessment. The construction sector remains one of the most resource-intensive domains, accounting for approximately 40%

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of global energy demand, up to 50% of extracted raw materials, and around 37.5% of the total waste generated in the European Union (EU) [1]. In response, European policy frameworks such as the European Green Deal [2], the Circular Economy Action Plan (CEAP) [3], and the Renovation Wave [4] increasingly emphasize the long-term improvement of the existing building stock.

Despite this policy momentum, the assessment of building performance remains fragmented in both research and practice. Durability is commonly addressed through domain-specific perspectives, including service life prediction, material degradation, hygrothermal behaviour, energy performance, or lifecycle assessment [5, 6], whereas resilience has developed mainly through risk-based frameworks focused on structural safety, climate adaptation, and post-event recovery [7]. As a result, the two concepts are often treated separately, even though both are directly related to the ability of buildings to maintain performance over time under changing conditions.

This separation is particularly relevant in the context of existing buildings, where renovation decisions must simultaneously address energy efficiency, structural reliability, service life extension, and adaptation to future risks. From a circularity perspective, this implies moving beyond short-term efficiency gains and considering the long-term preservation of building value, function, and performance while minimizing resource consumption and avoiding premature replacement or demolition [8]. In this regard, durability may be understood as the ability of a building, component, or material to maintain required performance under expected service conditions, including structural adequacy, envelope integrity, and energy-related behaviour [9]. Resilience, in turn, refers to the capacity of buildings and building systems to withstand, absorb, adapt to, and recover from disturbances such as earthquakes, floods, heatwaves, or energy supply disruptions [7]. While durability is associated with continuity of performance, resilience introduces a dynamic perspective centered on adaptive capacity and recovery.

This intersection is increasingly important in light of recent regulatory developments, including the recast Energy Performance of Buildings Directive (EPBD) [10], which reinforce the need for broader performance frameworks capable of informing renovation strategies beyond isolated technical targets. Against this background, this paper critically reviews how durability and resilience have been defined, interpreted, and operationalized in relation to structural and energy performance. The review aims to clarify their conceptual relationship, identify methodological overlaps and divergences, and discuss their integration within whole-life approaches to building performance.

The paper is based on a narrative and critical review of literature addressing durability, resilience, structural performance, energy performance and circular construction. The sources were selected to capture the conceptual evolution of these concepts and their integration within whole-life-cycle approaches. The review synthesizes key conceptual and methodological contributions in order to identify overlaps, gaps and directions for integrated assessment.

The following section examines the conceptual foundations of durability and resilience in circular construction, with emphasis on their relevance for structural and energy performance over time.

2 Conceptual Framework Analysis of Durability and Resilience in Circular Construction

In the context of reshaping the built environment, durability must be understood beyond its traditional association with material stability and service life alone [11]. In contemporary construction practice, its core meaning remains the ability of a building to maintain its essential functions, safety requirements, and technical performance throughout its intended service life [9]. This understanding is grounded in established frameworks such as ISO 15392 [12] and EN 15978 [13], which support the assessment of long-term material properties, structural capacity, and energy performance under normal operating conditions [14]. Within a circular construction perspective, however, such assessments cannot remain fragmented. They need to be integrated into a whole-life-cycle (WLC) framework structured around five interrelated dimensions: material, energetic, structural, economic, and social [5]. Rather than representing isolated metrics, these dimensions collectively support value retention, resource efficiency, and the prevention of premature obsolescence [11].

In this perspective, durability is relevant not only because it extends service life, but also because it preserves the functional and economic value of buildings through continued use, adaptability, and reduced replacement needs [15, 16]. This aspect is particularly important for existing buildings, where structural adequacy and energy-related performance must be maintained while accommodating changing regulatory, climatic, and operational demands.

Durability alone, however, is insufficient to address extreme climatic events and broader systemic disruptions. In this context, resilience has emerged as a complementary paradigm, defined as the capacity of a system to withstand shocks, maintain operational functionality under adverse conditions, and recover within an acceptable timeframe. This perspective has been advanced through performance-based seismic engineering and risk-informed design approaches [7]. At the same time, resilience literature increasingly links the concept to vulnerability, adaptive capacity, and recoverability, thereby extending its interpretation beyond resistance alone [17]. While durability addresses gradual and predictable degradation over time, resilience introduces a dynamic, hazard-oriented perspective focused on response, adaptation, and recovery [9].

An increasingly relevant component of resilience is passive survivability, namely the ability of a building to remain safe and habitable even in the absence of critical energy services [10]. Recent studies further relate this dimension to thermal resilience during heatwaves and power outages, showing that building performance should not be assessed only through operational energy savings, but also through indoor habitability under disruption [19]. This makes the intersection between durability and resilience particularly relevant in relation to structural reliability and energy performance, especially in the renovation of existing buildings.

A truly circular built environment ultimately requires stronger integration across disciplines and the development of frameworks that can support coherent decision-making in practice [9, 18]. Within such a perspective, durability and resilience should be regarded as complementary dimensions of building performance. Durability supports adaptive reuse, lifecycle optimization, and resource conservation, while resilience strengthens the ability of buildings and their users to withstand and recover from environmental

and socio-technical disturbances. Considered together, they offer a more robust basis for assessing whole-life building performance through the combined lens of circularity, structural reliability, and energy resilience [6].

3 Durability Pillars in the Circular Economy and Resilience Framework

To support the interpretation of durability within circular construction, the reviewed literature frames building performance through five interrelated pillars: material, energetic, structural, economic and social [5, 11]. Within this perspective, durability is understood as a multidimensional condition related to the long-term preservation of building performance, value retention, resource efficiency and reduced obsolescence across the building life cycle. Figure 1 illustrates the conceptual relationship between circular construction, durability, resilience, the five pillars and integrated performance outcomes.

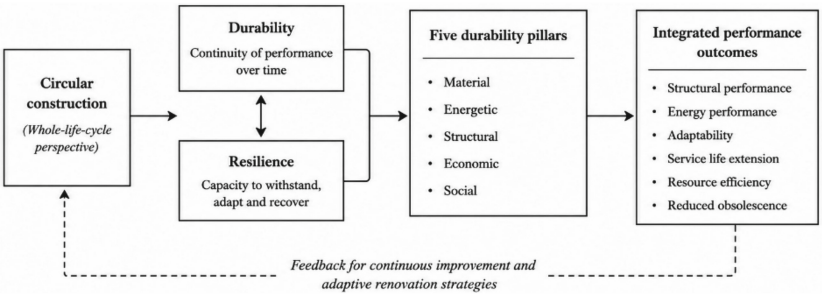


Fig. 1. Conceptual framework linking durability, resilience and whole-life-cycle building performance in circular renovation.

To clarify these relationships, Table 1 maps each durability pillar to the corresponding sustainability and circularity practices identified in the literature, while also highlighting their links to resilience-related outcomes. Although all five pillars contribute to whole-life building performance, the structural and energetic dimensions remain central to the present discussion, whereas the material, economic, and social dimensions are considered supporting factors that shape the long-term viability and wider implications of renovation strategies. A critical limitation of current approaches is that durability and resilience are often assessed through separate indicators, although their effects are interdependent in existing buildings. This fragmentation may lead to renovation strategies that improve one performance dimension while unintentionally compromising structural reliability, resource efficiency or long-term adaptability.

Table 1 further maps each durability pillar to circularity-oriented WLC practices and resilience-related outcomes.

The reviewed literature suggests that integrating these durability pillars requires a shift from fragmented design approaches toward more advanced digital and multicriteria assessment frameworks. In this regard, Building Performance Simulation (BPS) and

Table 1. Durability pillars in relation to circularity and resilience.

Durability Pillar	Circularity-oriented WLC practices	Resilience contribution
1. Material	Life Cycle Assessment (LCA) based reduction of embodied carbon [20]; use of biogenic or recyclable materials [10]; extended component lifespan to reduce raw material demand and construction waste.	Maintaining physical and mechanical integrity under aggressive environmental exposures and unpredictable climatic shocks [9].
2. Energetic	Implementation of nZEB/ZEB standards [20]; optimization of the building envelope and Technical Building Services (TBS) to reduce operational energy use over the building life cycle.	Ensuring thermal resilience, limiting overheating, and reducing reliance on active systems during energy grid disruptions.
3. Structural	Design for long-term structural integrity; functional adaptability and adaptive reuse of existing assets instead of demolition and new construction [8].	Providing robustness against extreme hazards (e.g., seismic events and extreme weather) to prevent collapse and reduce post-disaster downtime [7].
4. Economic	Life Cycle Cost (LCC) optimization; focus on long-term value creation and avoidance of premature obsolescence or replacement [11].	Ensuring financial stability by reducing the impacts of energy price volatility and post-disaster repair costs.
5. Social	Promotion of ethical, human-centred design; improved indoor environmental quality [19]; reduction of energy poverty and support for intergenerational equity [5].	Guaranteeing passive survivability, i.e., the ability of the building to remain safe and habitable for occupants during prolonged crises or heatwaves (evaluated via SET indicators).

digital twins, combined with LCA and LCC analyses, are increasingly used to support the joint evaluation of structural robustness, energy efficiency, and climate adaptation. Overall, these perspectives reinforce the need to interpret circularity and resilience as interrelated dimensions of whole-life structural and energy performance rather than as isolated design objectives [6].

4 Implications for Circular and Resilient Renovation

Building on the framework outlined in the previous section, the practical relevance of durability and resilience becomes most evident in the renovation of the existing building stock. In the European context, the main challenge is no longer limited to the construction of new high-performance buildings, but increasingly concerns the upgrading of aging and inefficient assets. A substantial share of the European building stock predates contemporary energy and structural standards: approximately 35% of EU buildings are

more than 50 years old, while nearly 75% remain energy inefficient. This aging profile reveals not only a major energy performance deficit, but also an increased vulnerability to climatic stressors and evolving performance requirements. At the same time, deep renovation rates remain critically low, at around 0.2% across the EU [4], reinforcing the need to translate broad sustainability objectives into practical and scalable renovation strategies. From a circular economy perspective, these conditions strengthen the case for shifting away from demolition-and-reconstruction models and toward adaptive reuse, service life extension, and performance upgrading of existing buildings.

Within this context, the integration of durability and resilience provides a useful interpretative basis for renovation decision-making. Considered through the five durability pillars and a whole-life-cycle perspective, renovation strategies can move beyond fragmented approaches in which structural safety, energy efficiency, material impacts, and occupant-related aspects are assessed separately. Such fragmentation is particularly problematic in existing buildings, where energy retrofit measures may affect not only thermal behaviour, but also the structural response, durability, and long-term serviceability of building components. Conversely, structural upgrading measures may influence envelope configuration, moisture behaviour, and the feasibility of energy-related interventions. Renovation strategies should therefore be assessed in terms of both trade-offs and synergies between structural reliability and energy performance over time.

One of the clearest examples is the tension between winter energy optimization and summer thermal performance. Although highly insulated envelopes may support compliance with nZEB/ZEB targets under the EPBD framework [10], such measures may also increase overheating risk if not accompanied by appropriate ventilation, shading, and adaptive design strategies [19]. A resilience-oriented perspective is therefore essential, as it extends energy renovation beyond efficiency targets alone to include passive survivability, namely the ability of buildings to remain safe and habitable during heatwaves or power interruptions. In this sense, energy-related durability becomes directly linked to occupant safety and functional continuity.

The literature also suggests that the large-scale implementation of such renovation strategies depends on overcoming the persistent dominance of initial-cost-based decision-making [4]. In this regard, LCC provides a more appropriate basis for evaluating renovation interventions, as it captures long-term economic performance rather than short-term affordability alone [7]. Investments in durable materials, adaptable TBS, and integrated retrofit measures may involve higher upfront costs, but they can reduce repair needs, delay obsolescence, and improve long-term value retention. From this perspective, circular and resilient renovation should be understood not as a collection of isolated technical upgrades, but as a long-term performance strategy that supports structural reliability, energy efficiency, reduced vulnerability, and value preservation over time.

5 Conclusions

This review has shown that the transition toward a sustainable and circular built environment depends largely on the renovation of the existing building stock. In this context, fragmented or isolated green interventions are insufficient to address current structural, energy, economic, and climatic challenges [11]. The analysis indicates that bridging

the gap between theoretical sustainability objectives and practical renovation strategies requires an integrated perspective in which durability and resilience are treated as complementary dimensions of whole-life building performance [6, 9]. Structured through five interconnected pillars, respectively material, energetic, structural, economic, and social [5], this perspective supports service life extension, value retention, resource efficiency, and reduced obsolescence across the WLC [14].

The review further suggests that circularity requires a shift from demolition-and-reconstruction practices toward renovation strategies better suited to the aging European building stock. In this regard, durability supports the long-term preservation of structural and energy-related performance under normal conditions [9], while resilience extends the assessment toward adaptability under climatic extremes and infrastructure-related disruptions [18]. Concepts such as passive survivability [10] and LCC [19] reinforce the need for renovation approaches that simultaneously address environmental performance, occupant safety, long-term functionality, and economic viability [18].

Future research should therefore focus on the operational integration of these dimensions through digital and multicriteria assessment methods. In particular, the use of predictive climate scenarios for the 2050–2080 horizon, together with BPS, Digital Twins, and composite performance metrics [19], may support a more robust evaluation of energy efficiency, structural robustness, and climate adaptation. Such approaches are essential for strengthening whole-life renovation strategies and advancing the sustainable, circular, and resilient rehabilitation of existing buildings [6].

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Design-for-Disassembly in Industrial Heritage Renovation: Methods and KPIs for Circular Decision-Making

Milena Rajić[1](✉), Meri Cvetkovska[2], and Pelin Sertyeşilışık[3]

[1] Faculty of Mechanical Engineering, Department of Management in Mechanical Engineering, University of Nis, Nis, Serbia
milena.rajic@masfak.ni.ac.rs

[2] Faculty of Civil Engineering, Ss. Cyril and Methodius University in Skopje, Skopje, North Macedonia

[3] Construction Department, Afyon Vocational School, Afyon Kocatepe University, Afyonkarahisar, Turkey

Abstract. Industrial buildings represent a significant component of the global building stock, contributing to global CO_2 emissions: in 2022, the building and construction sector accounted for around 37% of global energy- and process-related CO_2 emissions. Given the large embodied-carbon footprint associated with construction materials and structural components, there is urgent need for circular renovation strategies. Design-for-disassembly (DfD) offers an approach by enabling reversible interventions, component recovery, and material reuse instead of demolition. This paper proposes a KPI-based framework specifically customized for assessing circular performance in industrial building renovation. The framework is illustrated through a representative industrial building (IH-1) as a proof-of-concept, using circularity indicators drawn from literature, standards, and policy-oriented assessment logic. The proof-of-concept demonstrates the practical feasibility of structuring and comparing circular performance in existing industrial assets and provides a structured tool for comparing renovation scenarios, for evidence-based circular renovation strategies in industrial building stock. The methodology applies a circular KPI scoring matrix to evaluate multiple renovation scenarios, focusing on disassemblability, material recovery potential, and adaptability. Results show that the framework strengthens decision-making by revealing performance differences between renovation options and guiding practitioners toward circular strategies that improve resource efficiency and support long-term industrial building regeneration.

Keywords: Industrial Buildings · Circular Renovation · Design-For-Disassembly · Circularity Indicators · Resource Management · Material Recovery

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1 Introduction

The building and construction sector represents one of the most resource-intensive and environmentally impactful sectors globally. Recent assessments indicate that it accounts for approximately 37% of global energy- and process-related CO_2 emissions, positioning it at the center of climate change mitigation efforts [1]. Within the European context, the challenge is further intensified by the age and condition of the existing building stock. A considerable proportion of buildings were constructed before the implementation of modern energy performance standards and now require substantial renovation to meet contemporary environmental and functional requirements [2–4]. Industrial buildings are characterized by material-intensive construction, long spans, and durable steel or reinforced-concrete systems, contributing substantially to lifecycle resource use and embodied impacts [5]. At the same time, conventional redevelopment practices often rely on demolition and reconstruction, leading to considerable waste generation. Construction and demolition waste represents approximately one-third of total waste produced in the European Union, reflecting the inefficiencies of current linear approaches to building transformation [6]. Such practices not only result in the loss of valuable materials and embedded energy but also increase environmental burdens through additional resource extraction and emissions [7].

Industrial buildings also represent an important component of cultural and industrial heritage, embodying historical, architectural, and socio-economic values [8]. Despite their structural resilience and long service life, these buildings face significant challenges during renovation. Conventional approaches frequently involve partial or complete demolition of structural components, leading to substantial material waste and the irreversible loss of reusable elements [9]. Furthermore, the absence of design considerations for disassembly in many existing structures limits the potential for material recovery and reuse. As a result, renovation practices often fail to capitalize on the inherent value embedded within industrial buildings, while also neglecting the integration of circular economy principles [10]. The circular economy promotes resource retention, reuse, refurbishment, and material recovery instead of demolition-led redevelopment [11]. In industrial heritage renovation, circular strategies can reduce embodied emissions while improving adaptability and extending service life [12]. By prioritizing material recovery and reuse, circular renovation reduces the demand for virgin materials and lowers embodied carbon emissions. Additionally, adaptive reuse strategies improve building flexibility and resilience by enabling structures to accommodate changing functional requirements over time. A core concept supporting circular construction is design-for-disassembly (DfD), defined here as the intentional planning of building systems, components, and connections so that they can be separated, recovered, repaired, reused, or recycled with minimal damage and material loss. DfD enables buildings to be dismantled in a controlled and systematic manner, allowing components and materials to be recovered and reused [13]. Unlike traditional construction methods, where elements are often permanently fixed, DfD emphasizes reversible connections, modular design, and material separability. These principles facilitate efficient disassembly processes, improve material recovery rates, and reduce demolition waste [14]. Moreover, DfD improves adaptability by enabling buildings to be reconfigured or repurposed in response to evolving needs. Despite its potential, the application of DfD has been predominantly limited to new

construction projects, with relatively little attention given to its integration into the renovation of existing industrial buildings. Although significant progress has been made in the development of circularity assessment tools, lifecycle assessment methodologies, and DfD strategies, these efforts have largely focused on new building design rather than the renovation of existing structures [15]. Current frameworks, such as Level(s), provide valuable guidance for assessing sustainability performance but are not specifically tailored to the unique characteristics and challenges of industrial building renovation [16, 17]. There is a lack of systematic approaches for evaluating circular performance in existing industrial buildings, as well as limited methods for comparing alternative renovation scenarios using quantitative indicators. Furthermore, existing studies rarely integrate DfD principles with measurable performance metrics, which limits their applicability in practical decision-making contexts. In response to these gaps, this paper proposes a structured framework based on KPIs for assessing circular renovation strategies in industrial buildings. KPIs are defined as quantifiable metrics used to evaluate the performance of a system relative to defined objectives, and in this context, they enable the measurement of circular performance across multiple dimensions, including disassemblability, material recovery potential, adaptability, and resource efficiency. The proposed framework integrates DfD principles into a scenario-based evaluation approach, allowing for the systematic comparison of different renovation strategies. A representative industrial building is used as a proof-of-concept case to illustrate the applicability, transparency, and internal consistency of the framework, while recognizing that full empirical validation requires future testing on documented renovation projects.

2 Literature Review

The circular economy has emerged as a transformative paradigm aimed at decoupling economic growth from resource consumption by eliminating waste, circulating materials, and regenerating natural systems [18]. In the built environment, this approach requires a shift from conventional linear practices toward lifecycle-oriented strategies that prioritize durability, reuse, and recovery of materials and components [19]. Industrial heritage buildings provide a particularly relevant context for the application of circular economic principles. These structures are not only significant from a cultural and historical perspective but also represent substantial material reservoirs due to their resilient construction and long service life [8]. Adaptive reuse has been increasingly recognized as a sustainable strategy that allows existing buildings to be repurposed while avoiding the environmental impacts associated with new construction. Empirical research demonstrates that retaining structural elements can significantly reduce embodied carbon emissions by minimizing the need for new material production [9].

The main enabler of circular construction is the concept of DfD, which focuses on enabling buildings to be dismantled in a controlled and systematic manner, thereby facilitating material recovery and reuse. The international standard ISO 20887:2020 provides a comprehensive framework for implementing DfD and adaptability principles across multiple hierarchical levels, including systems, elements, components, and materials [12]. Previous studies highlight methodological challenges in assessing circularity and allocating environmental impacts across multiple reuse cycles, particularly during early-stage decision-making [13]. Consequently, KPI-based semi-quantitative approaches are

increasingly used for comparative circular assessment under data uncertainty. Despite these findings, the main limitation identified in the literature is the fragmentation of circularity indicators and the disproportionate focus on material flow metrics. Many existing frameworks emphasize quantities of recycled or reused materials while underrepresenting critical aspects such as adaptability, disassemblability, and long-term reuse potential [14]. There is a clear need for integrated assessment frameworks that combine DfD principles with comprehensive KPI systems specifically tailored to existing industrial buildings. Such frameworks would enable more effective evaluation of renovation strategies and support the transition toward circular and sustainable construction practices [20].

3 Methodology

A scenario-based circular performance assessment is applied in this study, specifically designed to support early- and mid-stage renovation decision-making processes, where detailed LCA inventories are often incomplete or unavailable. The methodology combines KPI selection, scenario definition, semi-quantitative scoring, and comparative aggregation of circular renovation performance. The development of the KPI framework is grounded in circular economy principles and DfD logic. Five KPI categories were defined: structural disassemblability, material recovery, component reuse, adaptability, and resource efficiency. Circular documentation and recovery strategies are informed by materials passport approaches developed within the BAMB project, which highlights the importance of structured information for enabling material recovery and reuse [17]. Policy alignment is ensured by linking these KPIs to European Union priorities on construction and demolition waste reduction and circular renovation strategies. The KPI definitions used in the assessment are summarized in Table 1. Each KPI category captures a specific aspect of circular performance, supported by measurable indicators and methodological anchors derived from standards, policy frameworks, and scientific literature.

A semi-quantitative scoring system is applied to evaluate each KPI category. Scores range from 1 to 5, where 1 represents very low circular performance and 5 represents very high performance. Scores range from 1 (low circular performance) to 5 (high circular performance), reflecting increasing levels of reversibility, reuse potential, and adaptability. The use of a simplified scale enables practical application in situations where detailed quantitative data are not available, while still providing meaningful differentiation between renovation scenarios. All KPI categories are assigned equal weights in the baseline assessment, unless project-specific stakeholder priorities suggest otherwise. The aggregated circular performance score for each scenario is calculated using Eq. (1), which represents a weighted average of individual KPI scores:

$$S_j = \frac{\sum_{k=1}^{5} w_k \; s_{k,j}}{\sum_{k=1}^{5} w_k} \tag{1}$$

where $s_{k,j}$represents the score of KPI category $k$under scenario j, and $w_k$represents the weight assigned to each KPI category. Under equal weighting conditions, where $w_k = 1$,

Table 1. KPI definitions used in the assessment

KPI category	Definition	Typical evidence for scoring	Primary methodological anchors
Structural disassemblability	Ability to separate structural systems with minimal damage	Reversible connections; accessibility of joints; independence of layers	ISO 20887 principles [12]
Material recovery	Ability to recover materials into high-value loops	Selective dismantling plans; waste segregation; recovery paths	EU waste and renovation policy [6, 7]
Component reuse	Direct reuse potential of building elements	Standardization; deconstruction feasibility; recertification paths	Structural reuse studies [9]
Adaptability	Capacity for functional transformation with minimal intervention	Flexible layouts; modular partitions; service zoning	ISO adaptability principles; Level(s) [12, 15]
Resource efficiency	Reduction of virgin material use and waste generation	Retained structure ratio; recycled content; waste reduction	Circular economy policy and Level(s) [11, 15]

Eq. (1) simplifies to the arithmetic mean of the five KPI scores. Eq. (1) defines the overall circular performance of each renovation scenario and enables direct comparison across alternatives. The assessment is intended as a proof-of-concept rather than a fully validated empirical case study. IH-1 therefore represents a typical industrial building model used to test the consistency and applicability of the KPI framework under limited-data renovation conditions. Future work should validate the framework using real renovation projects and BIM-based inventories. The case study is based on a representative industrial building, referred to as IH-1, which serves as a proof-of-concept model for the proposed framework. Given the absence of a specific real-world building dataset, IH-1 is defined as a typical industrial hall in Southeast Europe. It is characterized as a single-storey structure with a long-span structural system, typically consisting of steel portal frames or truss configurations commonly used in industrial construction. The building envelope is assumed to consist of mixed cladding and masonry systems typical of legacy industrial facilities, while building services are considered to have undergone multiple upgrades over time, resulting in partial obsolescence. This representation is consistent with the heterogeneous nature of non-residential building stock, which includes diverse industrial and warehouse typologies with varying material and energy characteristics (Table 2).

Three renovation scenarios are defined to evaluate different levels of circularity integration. The first scenario represents conventional renovation practices, involving partial demolition, replacement of structural elements, and limited material recovery.

Table 2. Representative construction characteristics of IH-1 and relevance for scenario scoring

IH-1 characteristic	Representative assumption	Relevance for scenarios and KPI scoring
Structural system	Steel portal-frame/truss industrial hall	Affects reuse and disassembly potential across scenarios
Connections	Mixed bolted and welded legacy connections	Influences reversibility and disassembly efficiency.
Building envelope	Mixed masonry infill, aged cladding panels, and roof covering with different levels of separability	Influences material recovery and waste generation. Scenario 1 replaces mixed assemblies; Scenario 2 selectively dismantles recoverable parts; Scenario 3 uses modular and separable envelope interventions.
Services	Electrical, ventilation, and utility systems upgraded over time, with partial obsolescence and limited documentation	Affects adaptability and future maintenance. Scenario 3 introduces service zoning, documentation, and easier access for future replacement.

The second scenario reflects circular renovation principles, incorporating selective dismantling, increased reuse and recycling of materials, and partial retention of structural components. The third scenario represents a DfD approach, emphasizing reversible connections, modular interventions, maximized component reuse, and systematic planning for future disassembly through documentation and information transfer.

4 Results and Discussion

The circular performance of the three renovation scenarios was evaluated using the KPI framework presented in Sect. 3. The results are summarized in Table 3, which reports proof-of-concept scores for the representative industrial building (IH-1). The scoring reflects the evidence logic defined in Table 1 and typical differences between demolition-led renovation practices and circular and DfD approaches. The results show a clear improvement in circular performance from Scenario 1 to Scenario 3. The conventional renovation scenario achieves the lowest score due to its reliance on partial demolition and replacement, which typically involve irreversible connections and mixed-material assemblies that limit disassembly and reuse potential. This outcome is consistent with the principles outlined in ISO 20887, which emphasize the negative impact of non-reversible construction methods on circular performance [12]. The circular renovation scenario shows moderate improvement, particularly in material recovery and resource efficiency, due to the implementation of selective dismantling and improved waste management practices.

Table 3. Circular KPI category scores for IH-1

KPI category	Scenario 1 Conventional	Scenario 2 Circular	Scenario 3 DfD
Structural disassemblability	2	3	5
Material recovery	2	4	4
Component reuse	2	3	5
Adaptability	3	3	4
Resource efficiency	2	4	4
Aggregated score (S_j)	2.2	3.4	4.4

Scenario differences are directly linked to IH-1 construction characteristics. Scenario 1 scores lowest due to demolition-led replacement and limited recoverability. Scenario 2 improves material recovery through selective dismantling and retention of structural elements. Scenario 3 achieves the highest circular performance through reversible connections, modular interventions, and planned future disassembly.

5 Conclusion

This paper shows that circular renovation strategies for industrial buildings can be systematically evaluated using a KPI-based framework that integrates DfD principles. The results from the representative industrial building case (IH-1) show that the DfD-based renovation scenario significantly outperforms both conventional and partially circular approaches, particularly in terms of structural disassemblability and component reuse potential. The proposed methodology provides a transparent and practical decision-support tool that can be applied in early-stage renovation planning, where data availability is often limited. However, the presented IH-1 application should be interpreted as representative proof-of-concept rather than a fully empirically validated case study. The main limitation is the absence of a complete as-built material inventory, detailed connection survey, and measured post-renovation data. Future work should test the framework on real industrial heritage renovation projects, include expert-based weighting of KPIs, and integrate BIM or material passport data to improve scoring accuracy and validation resilience. The approach is adaptable and can be extended to multiple case studies, integrated with BIM, and linked with lifecycle assessment methods to provide more comprehensive sustainability evaluations.

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Towards Distributed and Circular Construction: Pop-up Factories as Hybrid on-Site Manufacturing Models

Federica Pradella(✉), Giorgio Castellano, and Ingrid Maria Paoletti

Politecnico di Milano, Piazza Leonardo da Vinci 32, Milan 20133, Italy
federica.pradella@polimi.it

Abstract. The increasing complexity of architectural projects and the demand for circular and resource-efficient practices are driving exploration of decentralised production models for the built environment. Among these, pop-up factories represent a temporary production paradigm situated between off-site prefabrication and traditional on-site construction. Their implementation requires an integrated assessment of technical, environmental, and regulatory factors, helping to evaluate their potential to reduce logistics, activate local supply chains, and enable circular material flows. This research proposes a conceptual assessment framework for pop-up factory planning in the early design stages. The study adopts a qualitative and exploratory approach, combining a literature review, selected case studies of Distributed Manufacturing (DM), Design for Manufacturing and Assembly (DfMA), and regulatory benchmarking within European policies. Variables influencing system performance are identified and grouped into three categories: technical-operational conditions, environmental and socio-economic considerations, and regulatory and governance constraints. The resulting screening tool supports stakeholders in assessing temporary factories under specific project conditions, from renovation to new construction. By organising the interaction between design characteristics, manufacturing constraints, local resources, and regulatory frameworks, the model contributes to more distributed, circular, and context-sensitive construction approaches.

Keywords: Pop-up Factories · Distributed Manufacturing · Circular Construction · Hybrid On-site Manufacturing · Evaluation Framework

1 Introduction

The Architecture, Engineering, and Construction (AEC) sector is undergoing significant transformations [1], driven by the need to reduce environmental impacts and respond to economic and social pressures. This transition is influenced by European policy frameworks such as the European Green Deal [2] and the Circular Economy Action Plan (CEAP), which promote the transition towards more resource-efficient and low-carbon construction systems [3]. However, compared with other industrial sectors, construction is characterised by much slower processes of evolution due to the high customisation of

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buildings and project-based workflows, which limit continuous improvement and subsequently hinder large-scale adoption of innovative and sustainable practices [4]. As a result, the sector relies on heterogeneous manufacturing paradigms, ranging from industrialised approaches which offer fundamental tools for more efficient and circular design and production processes [5] to craft-based practices that remain widespread in many contexts. Nevertheless, construction remains among the most resource-intensive industries in terms of material consumption, waste generation, and greenhouse gas (GHG) emissions [2].

Modern Methods of Construction (MMC) have historically addressed challenges in productivity, quality control, and resource management, particularly in projects involving multiple stakeholders [6]. However, centralised off-site production is often hindered by high investment costs, supply chain dependency, and logistical constraints, limiting the adaptability to diverse project scales and local conditions [7–9]. Conversely, Small and Medium Enterprises (SMEs)-led projects typically rely on on-site work for its flexibility and adaptability, but often remain affected by inefficiencies, fragmentation, and limited capacity to integrate innovation and low-carbon practices.

In response to these limitations, increasing attention has been directed towards decentralised production models capable of adapting to local constraints, temporary project conditions, and fragmented supply chains [4], while redistributing production capacity closer to construction sites, local value chains and material flows [10]. Within this context, the pop-up factory arises as a hybrid, temporary, and site-specific manufacturing system bridging off-site prefabrication and on-site construction [11–13]. Supported by Design for Manufacturing and Assembly (DfMA), and Distributed Manufacturing (DM) approaches [12], it enables more adaptable production configurations and closer integration between design, fabrication, and construction. Despite growing interest in decentralised production models, existing research has mainly focused on technological aspects or isolated case studies, while integrated approaches for evaluating their feasibility in construction projects remain limited.

To address this gap, this study proposes a conceptual evaluation framework for assessing pop-up factories in early-stage construction planning, integrating technical, organisational, economic, and regulatory factors. The approach aligns with the European Union (EU) policy landscape, including the Level(s) framework [14, 15], and the new EU Construction Products Regulation (CPR) [16]. The research contributes to the emerging debate on decentralised manufacturing in construction by introducing a multi-domain decision logic that connects design, production, and regulatory considerations.

2 Research Design and Method

The research adopts a qualitative and exploratory multi-criterion methodology that combines literature review, case study exploration, and regulatory benchmarking. The literature review addressed Industrialised Construction (IC) [4], DfMA, DM [17], mobile production models [11], and circular construction strategies, using scientific databases (e.g. Scopus and Web of Science). Exploratory case studies of decentralised production systems were examined (Table 1) [18, 19], while policy and regulatory documents were analysed to identify relevant environmental and circularity indicators. By comparing literature, case study characteristics, and regulatory indicators, recurring factors

influencing decentralised production feasibility were identified. An iterative process of abstraction and synthesis translates these factors into framework variables, clustered into three evaluation dimensions to ensure a comprehensive decision-support logic.

Table 1. Illustrative comparison of selected decentralised manufacturing cases [18, 19].

Equipment	Workforce	Logistics	Digital integration	Circular strategies
Case study, small scale: WikiHouse				
CNC router(s) standardized digital fabrication workflows	Local network of partners	Delivery of material, storage, fabrication, waste collection, assembly, component storage, loading	Open-source CAD-CAM data and file-to-factory workflows	Nesting strategies; dry assembly; possible disassembly; offcut reuse and recycling
Case study, large scale: Assembly OSM				
Industrialised component production systems Assembly-oriented technologies	International network of experts	Integrated off-site/on-site production workflows and coordinated supply systems	Digital coordination across project fabricators	Electric off-site facility; waste and CO_2 reduction through off-site production; supply chain management

3 Evaluation Framework for Pop-Up Factory Planning

Given the multi-domain nature of on-site manufacturing systems, the framework operates on two complementary levels: variables describe the functional nature of the parameters of the pop-up factory configuration, while clusters evaluate the domain through which each variable is assessed.

3.1 Variables Inventory

The first level includes 13 variables (Table 2) categorised as design, enabling, and boundary variables. These support a qualitative feasibility assessment of decentralised production systems and may be adapted according to site-specific project conditions.

Design Variables. This group of indicators describes the physical and operational characteristics of the production environment. Size is a primary parameter and varies depending on the application field, including new construction, renovation, temporary works,

and emergencies. According to the production requirements and component types, pop-up factories may be configured as small, medium, and large units. Spatial context concerns the organisation of the site into functional areas, including delivery, storage, fabrication plants, assembly, waste collection, and final product loading [10]. The hybrid nature of the model requires the integration of different materials and equipment, opening opportunities for locally sourced bio-based and waste-derived materials, and the integration of both traditional and advanced technologies [20].

Enabling Variables. These support the implementation of the system by improving coordination, innovation, and adaptability. Digital integration through Building Information Modelling (BIM), Digital twin (DT), and Artificial Intelligence (AI)-based optimisation can improve information flow and material traceability [21]. In parallel, site management strategies, potentially supported by drones and automated monitoring systems, improve scheduling, logistics control, and emissions tracking [20].

Boundary Variables. Safety requirements and regulatory compliance define the external constraints of the system. On-site safety must comply with national construction site regulations, while regulatory compliance embraces both production activities and component performance. At the EU level, the CPR prioritises digital traceability and circular economy principles through environmental performance declarations and digital product passports [16]. Renewable energy integration is also considered a sustainability-related condition. At this stage, no fixed minimum renewable energy threshold is proposed; the variable is qualitatively assessed as low/partial/high integration, ranging from grid-dependent temporary production to on-site temporary generation.

Table 2. Variables and indicators of the pop-up factory feasibility framework.

Variable	Evaluation cluster	Data type	Assessment mode	Indicator reference
Size	Technical-operational	Quantitative	Selection	–
Spatial context	Technical-operational	Qualitative	Selection	–
Project duration	Technical-operational	Scoring	Weighted scoring	–
Type of work activities	Technical-operational	Qualitative	Selection	–
Type of materials	Environmental and socio-economic	Scoring	Weighted scoring	Level(s) indicator 2.2
Application field	Environmental and socio-economic	Qualitative	Selection	Level(s) indicator 2.4
Equipment	Technical-operational	Qualitative	Weighted scoring	–
Logistics	Environmental	Scoring	Scoring	CO_2 reduction indicators

(*continued*)

Table 2. (*continued*)

Variable	Evaluation cluster	Data type	Assessment mode	Indicator reference
Workforce skills	Socio-economic	Scoring	Scoring	–
Digital integration	Technical-operational	Qualitative	Annotation	EU CPR 2024/3110
Site phasing	Technical-operational	Binary	Tick-box	–
Safety compliance	Regulatory	Binary	Tick-box	National law
Energy autonomy	Environmental	Qualitative	Annotation	EU Green Deal

3.2 Variables Clustering and Framework Structuring

The variables are grouped into three evaluation domains (Table 2).

Technical and Operational Conditions. These assess the compatibility and adaptability between design variables and different construction scenarios [14].

Environmental and Socio-Economic Considerations. This second layer evaluates CO_2 reduction, activation of local supply chains, workforce availability on-site and near-site, circular material flows, and supporting SMEs' access to innovation, in line with the European Sustainability Reporting Standards (ESRS) E1, E5, S2 and S3 [22].

Regulatory and Governance Constraints. The third layer investigates the alignment with current EU and national regulations, including CPR, Criteri Ambientali Minimi (CAM), and Life Cycle Assessment (LCA) protocols, identifying enabling or limiting conditions for system deployment to pursue sustainability targets.

4 Decision Support Logic for Feasibility Assessment

The framework operates through a cascade system. Variables are interpreted in relation to site-specific conditions, allowing stakeholders to identify enabling factors and potential constraints for pop-up factory implementation. The decision support logic is ensured by associating each variable with a data type and an assessment mode, allowing its interpretation within one of the three evaluation clusters. At this preliminary stage, assessment methods are expert-informed based on relevance to project constraints, contribution to circularity, and impact on regulatory viability. First, a preliminary resource mapping, identifying available materials, equipment, technological capabilities, and know-how available close to the construction site is performed. This supports renovation scenarios, fostering re-action practices and material audits, and new construction, helping in identifying local supply chains and stakeholders [23]. Afterwards, the information collected is

integrated into the design stage, in which material quantities, production requirements, and construction constraints are defined. Finally, the framework is applied to evaluate the applicability of the pop-up factory model, supporting a multi-criteria comparison between conventional construction workflows and a decentralised scenario (Fig. 1) [24].

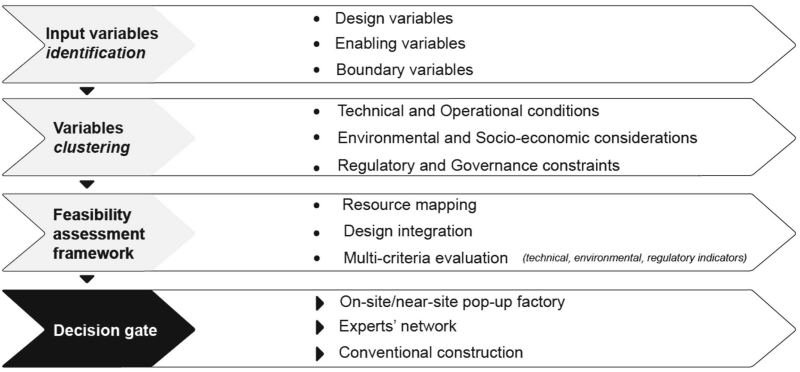


Fig. 1. Cascade-based decision-support framework for assessing pop-up factory feasibility in construction projects.

5 Application Example

Although the framework is primarily conceptual, it can be illustrated through two typical situations. In the deep renovation of public housing buildings in dense urban contexts, medium–long project duration and high logistics constraints may favour on-site sorting, remanufacturing, and reuse practices [14]. In new developments with limited industrial supply chains and high transport distances, near-site manufacturing may support the production of customised components while reducing logistics and transport-related impacts. In both cases, the framework does not provide a deterministic yes/no outcome but rather supports a comparative screening between alternative production configurations, including on-site, near-site, and conventional models, highlighting bottlenecks, such as workforce skills, energy autonomy, and safety constraints (Fig. 1).

6 Discussion

The results suggest that the performance of pop-up factories is not only a technical matter but requires a systemic understanding of multiple factors, including regulatory conditions, site-specific constraints, circularity principles, and stakeholder involvement [25]. By structuring the variables within an integrated evaluation system, the research contributes to advancing decision-support approaches for decentralised and hybrid manufacturing systems in construction.

A key finding is the importance of preliminary resource mapping. Identifying locally available materials, machinery, and expertise allows potential synergies to be evaluated

among design requirements and production capabilities. In renovation projects, this preliminary inventory may facilitate material audits and re-action practices [14, 15], whereas in new construction, it can activate local supply chains and networks of experts and SMEs [26]. At the same time, the coexistence of manufacturing and construction activities within the same perimeter necessitates complex planning, requiring coordination of material flows, logistics, and safety procedures. Digital integration may play a cross-cutting role in supporting this coordination, enabling real-time process monitoring. Dismantling is also relevant: temporary foundations, service connections, storage units, and design and production shelters should be conceived as reversible elements to avoid permanent site disturbance. Beyond transportability and modular set-up stored in standard containers [11, 27], further framework developments should consider circularity aspects such as the residual value of equipment and the reuse potential of the temporary production infrastructure across multiple projects.

The widespread diffusion of pop-up factories depends not only on technological readiness but also on the ability of regulatory frameworks to accommodate hybrid production models. EU initiatives such as the CPR and Level(s) may progressively improve distributed and traceable production systems. From an industry perspective, the proposed framework supports stakeholders in evaluating the applicability of pop-up factories in specific project planning contexts, fostering the use of local resources, reducing logistics, and supporting circular material flows. However, limitations are mainly related to the lack of validation through real construction projects and quantitative data. The proposed weighted scoring is preliminary and currently relies on expert-informed judgement; future research will concentrate on developing a scoring system based on design data and EU indicators. Overall, pop-up factories may be interpreted not only as a technical innovation but also as a potential catalyst for more adaptive, circular, and locally embedded construction practices.

7 Conclusion

Within the current transformation of the construction sector, the demand for hybrid manufacturing models that integrate industrial efficiency with site-specific constraints is becoming increasingly evident. In this context, pop-up factories should not be interpreted merely as temporary production infrastructures, but rather as a comprehensive operational ecosystem integrating physical resources, organisational processes, and regulatory conditions. This research provides a conceptual and methodological contribution to the ongoing discussion of decentralised manufacturing in construction by proposing a structured framework for evaluating the feasibility of pop-up factories during early-stage project planning. By integrating design, manufacturing, construction, and logistics in a unique site-based ecosystem, the framework highlights the potential of decentralised production systems to respond to local needs and to strengthen regional construction ecosystems, especially in SME-dominated contexts. Further research will focus on the validation and refinement of the framework through real-world application, enabling a more systematic comparison between decentralised and conventional construction configurations.

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Integrating Urban Mining and Reuse in the Design of a Circular Façade Renovation Module

Thaleia Konstantinou[1(✉)], Magdalena Zabek[2], and Vanesa Bano[3]

[1] Faculty of Architecture, Department of Architectural Engineering and Technology, Delft University of Technology, Julianalaan 134, Delft 2628, The Netherlands
t.konstantinou@tudelft.nl

[2] Faculty of Architecture and Civil Engineering, TU Dortmund University, August-Schmidt-Straße 8, 44227 Dortmund, Germany

[3] InnovaWood, 66 Rue du Luxembourg, 1000 Brussels, Belgium

Abstract. The construction sector is a major contributor to global environmental pressures, responsible for 40–50% of resource extraction, 60% of waste generation, and roughly one-third of CO_2 emissions. Transitioning to a circular economy (CE) is an essential pathway to resource efficiency and carbon reduction. Urban Mining (UM), as the systematic recovery of materials and components from the built environment, offers significant potential to reduce embodied impacts and resource dependency. However, the integration of UM into renovation and new-build design processes remains limited, particularly for industrialised façade systems, where modularity could enable more circular practices. This paper presents a UM-based approach for circular façade renovation, with a focus on the recovery and direct reuse of legacy resources that avoid the embodied energy of new production. Evidence shows that reused components consistently demonstrate lower Global Warming Potential (GWP) and primary energy demand compared with recycled or virgin materials. A modular, multifunctional façade renovation system is used as a case study to evaluate component recoverability, technical suitability, and logistical feasibility. Alternative materials for insulation and cladding is evaluated concerning their potential as reused or recycled resources. Applied to a school renovation project, reclaimed resources are integrated in the process for the cladding design strategies. Findings demonstrate that UM can support scalable, modular renovation solutions aligned with broader sustainability goals.

Keywords: Renovation · Façade · Circularity · Reuse · Urban Mining · Design process

1 Introduction

The construction sector remains one of the most resource-intensive industrial domains, responsible for 40–50% of global raw material extraction, 60% of waste generation, and nearly one-third of total CO_2 emissions. These numbers place the sector in a pivotal position for the current climate and resource-efficiency agendas, making the transition toward

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a circular economy (CE) a necessity. This transition is commonly interpreted through frameworks such as Cradle-to-Cradle [1] and the R-strategies, prioritizing reduce, reuse, recycle, repair, refurbish, remanufacture, and repurpose [2].

Within building life cycles, material production represents a major environmental impact, contributing up to 50% in new and low-energy buildings [3]. Among building subsystems, façades are particularly critical because they influence both operational energy demand and embodied carbon. Although their mass is relatively limited compared with structural systems, façade systems account for 10–30% of total embodied carbon emissions [4]. Consequently, façade design is of strategic importance in reducing environmental burdens while maintaining performance requirements.

This challenge is amplified in the renovation of existing buildings, which must be achieved at scale. More than 85% of Europe's building stock does not comply with current energy-efficiency standards. Achieving net-zero targets requires deep renovation that reduces energy demand by 60–90%, and double the annual renovation rates by 2030 [5]. Modular and industrialized renovation can support in achieving these objectives [6]. Yet, large-scale façade retrofitting may intensify material demand, and the related environmental burdens, unless circular strategies are embedded from the earliest design stages [7].

Reuse and recycling of existing components reduce end-of-life impacts while avoiding the production of virgin materials, thereby extending material utility according to CE principles. Urban Mining (UM), understood as the systematic recovery of materials and components from existing buildings, offers significant potential to reduce embodied impacts and dependence on primary resources. However, its implementation in façade renovation remains limited, despite industrialized systems' modularity could facilitate component recovery, replacement, and future reuse.

This paper addresses that gap by presenting a UM-based approach for circular façade renovation, focusing on the recovery and reuse of legacy resources as substitutes for primary materials. Legacy resources refer to materials that are no longer in active use and are undergoing the process of being repurposed into new products or application, on the original site, at a different location, or through transfer to another party for future reuse [3]. The study discusses the feasibility of secondary resource reuse in a modular façade renovation system, by evaluating the potential of alternative materials for insulation and cladding. moreover, the paper presents how the design process of a school renovation particularly regarding the selection of the cladding material for the modular system integrated UM consideration.

2 Methodology

The methodological approach aims to assess the integration potential of legacy resources within a modular façade renovation system under an UM perspective.

1. **Analyse material recovery potential for the insulation and cladding of the façade system**

   The approach is applied to the AEGIR [8] façade system, an industrialised, modular renovation solution based on a structural mesh comprising vertical and horizontal load-bearing elements. Each module (Fig. 1) integrates internal and external

enclosures, structural elements, insulation, and cladding, while selected applications incorporate photovoltaic panels, automated windows, and shading systems. Next to the objective of energy upgrade, the development of the module aims to improve the resource efficiency of the renovation, with the use of circular design principles. The modular configuration future disassembly makes it a relevant case for investigating how UM principles can support circular façade renovation at scale. The study focuses on the material selection considerations, by, firstly, conducting a systematic inventory of alternative materials for the insulation and cladding components.

2. **Exploring the complexity of implementing reclaimed materials in a Case-study application**

   The framework is tested in a school renovation case study in Spain (Fig. 2), where the modular façade system is applied to increase the energy performance and thermal comfort. This study focuses on the material selection process for cladding.

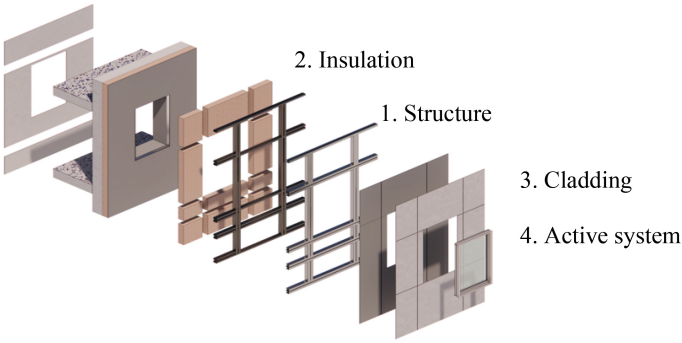


Fig. 1. Exploded view of the modular façade system AEGIR (Image courtesy of AEGIR project and UN Studio).



Fig. 2. The case study, an educational building in Margrat, Spain (source: project AEGIR [8])

3 End-of-Life (EoL) Potential for the Insulation and Cladding Component of the Modular Renovation System

To evaluate the potential for UM, the different components of the systems need to be investigated separately. The study further focuses on the alternative materials and their End-of-Life (EoL) scenarios of insulation and cladding, in particular.

3.1 Insulation

The selection of insulation materials is critical for circular façade design, influencing embodied impacts, recoverability, and EoL pathways. Biobased and recycled, post-consumer material alternatives offer improved environmental performance compared to conventional materials, but their circularity depends on composition, installation, and recovery strategies.

Biobased Insulation – Cellulose: Cellulose insulation, produced from recycled paper, offers low embodied energy and strong reuse potential, particularly in loose-fill applications where non-destructive removal is possible. However, the use of borate-based fire retardants limits recyclability and compatibility, while also raising health concerns during installation. Its circular performance therefore depends on reversible installation methods and reduced reliance on hazardous additives.

Biobased Insulation – Wood Fiber: Wood fibre insulation provides the benefit of carbon storage and is suitable for façade applications due to its panel format. While reuse and composting are theoretically possible, the presence of additives such as paraffin and synthetic binders often limits these pathways. In practice, energy recovery remains the dominant EoL route. Improving circularity requires minimizing additives and enabling mechanical disassembly.

Textile-Based Insulation: Textile insulation utilizes recycled fibres, contributing to waste valorisation and offering good handling properties. However, its circularity is constrained by the use of synthetic binders and the environmental impacts of the original textile production. Although recyclable, it is often downcycled or landfilled in practice. Design strategies should focus on maintaining material purity and enabling efficient recovery.

PET-Based Insulation: PET insulation incorporates recycled plastic fibres and benefits from existing recycling systems, including take-back schemes. Despite this, actual recycling rates remain limited (47%) due to collection and contamination challenges. As a fossil-based material, its sustainability is conditional on effective recycling. Design for disassembly is essential to improve recovery and maintain material value.

3.2 Cladding

The modular façade system has the possibility to apply different types of cladding materials, making the renovation adaptable to the project's ambition, context, design intent, environmental consideration, as well as circularity. Common cladding materials,

such as metals, timber, composites and concrete, were examined as legacy resources, with regard to reuse and recycling.

Aluminium and Steel: Metals exhibit high circularity potential due to their ability to be recycled with minimal quality loss. Aluminium recycling potential is well-established. The 75% of the aluminium produced to date is still in use today due to its infinitely recyclable properties. In 2018, over 90% of the aluminium used in the transportation and construction sectors was recovered [9]. Despite strong recycling systems, direct reuse of structural elements remains limited. From a design perspective, circularity depends on material traceability, standardised components, and reversible connections to enable high-quality recycling or reuse.

Timber: Timber follows a cascading use model, where recycling often results in down-cycling into lower-value products such as chipboard [10] . Material quality is affected by coatings, preservatives, and contamination, limiting recycling potential. In contrast, reuse of structural timber offers higher circular value, particularly for large sections that can be reprocessed or integrated into engineered wood products [11]. However, most demolition wood is currently incinerated. Design strategies should prioritise non-destructive disassembly, minimise chemical treatments, and preserve structural dimensions to enable reuse and maintain material value across multiple life cycles.

Concrete: Concrete recycling is widely practised, with most waste processed into aggregates for low-value applications such as road construction. This represents down-cycling, as only a small share is reused in new concrete due to quality and contamination constraints. Reuse of concrete elements offers higher circular potential by preserving structural integrity and embodied energy, but requires selective deconstruction and adapted connection design [12]. This requires the careful disassembly of outdated structures into relatively large pieces, employing methods such as a diamond saw or high-pressure waterjets. To improve circularity, design approaches should focus on modularity, standardisation, and reversible connections to facilitate future recovery and reuse.

4 A Case Study of Urban Mining Considerations in the Design Process of a School Renovation

The discussed Urban Mining (UM) considerations were integrated into the renovation design of a school building serving as the Spanish demonstration site. As part of the circular design strategy, alternative materials with lower embodied environmental impacts were explored for the cladding layer of the modular renovation system, which required further specification in the context of this project. In particular, the building owner expressed interest in exploring reclaimed timber as a façade cladding solution, prompting a more detailed assessment of reuse opportunities, utilising the UM considerations and reclamation routes. To support the design decision, the material selection process considered multiple criteria, including durability, availability, and economic feasibility.

4.1 Identification of Reused Timber Sources

To evaluate the feasibility of reused timber within the façade system, a systematic search for potential material sources was conducted. This process included both local supply investigations and digital platform screening. Local material suppliers located near the construction site were contacted, in order to identify reclaimed timber streams originating from demolition activities or secondary material markets. The suppliers were asked to provide information regarding available material volumes, dimensions, species, and expected delivery timelines. Furthermore, digital material exchange platforms were explored as additional procurement channels.

Following this market screening for availability, three representative timber sources were selected for further analysis: demolition timber, pallet wood, and eucalyptus elements recovered from mussel farm structures. Details on the volume, price and maintenance are shown in Table 1.

Table 1: Reclaimed wood sources

Product	Timber from building demolishing	Pallets	Eucalyptus from mussel farms
			
Volume	limited	Available within 1 year	Available within 1 year
Price (€)	€100/m	€26/m^2 + 20 €/h work (1200 €/m^3 + 20 €/h)	€37/m^2 (700–1300 €/m^3)
Durability	No naturally durable wood (pine)	No naturally durable wood	Moderately durable

4.2 Durability and Additional Design Considerations

For the timber cladding application of this project, resistance to weathering and fungal decay represents a critical design parameter. The durability of wood species is classified according to EN 350–2, which defines natural resistance to biological degradation. Several wood species relevant to the Spanish region were considered as reference materials for comparison with reused timber. These include sweet chestnut, European oak, and Douglas fir.

Timber recovered from building demolition can consist of both durable species, such as oak and chestnut, and non-durable species, such as pine, depending on the original building. These elements often originate from beams or rafters and require reprocessing into suitable cladding dimensions, increasing labour effort but enabling adaptation to modular façade systems.

Pallet wood represents another potential source of reclaimed timber. Pallets are typically manufactured from pine or poplar and therefore lack natural durability against biological degradation. However, they are often available in standardised sizes and can be processed into façade cladding elements with relatively low material costs. Additional protective treatments are required when such materials are used in exterior conditions.

The third identified material stream consists of eucalyptus elements recovered from mussel farming structures. These components are typically available as planks of approximately 40–50 mm thickness and 150–200 mm width. The wood species exhibits moderate durability and can therefore be applied in protected façade areas or where architectural design features such as overhangs reduce direct weather exposure. Thus, durability depends not only on material properties but also on façade detailing. Strategies such as protected placement, ventilation, and surface treatments are essential.

Finally, due to the difficulty in finding naturally durable reused wood from the same supplier in quantity enough and to address the challenges associated with sourcing a sufficient volume of reclaimed wood, a strategic decision has been made to utilise reclaimed wood in a limited amount and in areas which are protected from weather. In this way, no treatment will be needed in the wood for cladding, but a superficial protection (a coating commercially named "lasur"). It is estimated that up to 27% can be reused [13], as a third life strategy. For the exposed areas, biobased composite panels were selected for their reduced environmental impact as they are crafted from natural, renewable components like plant fibres or agricultural waste, which are then combined with biobased resins. Figure 3 illustrates the placement of the materials and the considerations for their life-cycles.

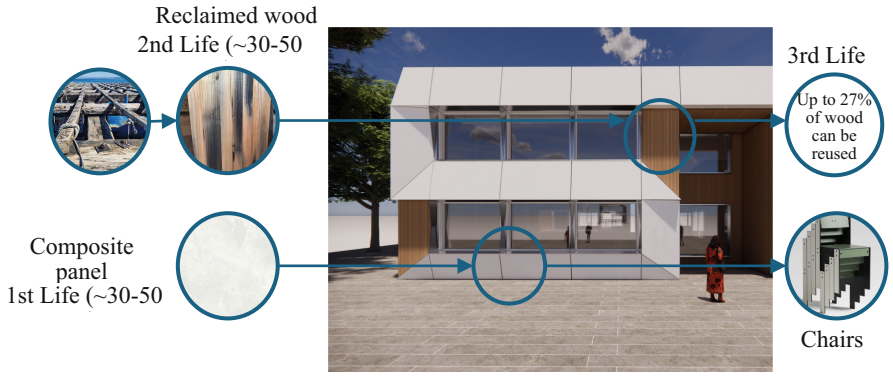


Fig. 3. Resulting material selection for timber cladding of reclaimed and treated Eucalyptus from mussel farms and biobased composite, with the AEGIR system application (Image courtesy of AEGIR project and UN Studio).

5 Conclusion: Impact of UM in Circular Façade Design

The study demonstrates how Urban Mining principles can be integrated into the design process of façade renovation systems. From a circular design perspective, early identification of available legacy resources is essential. By integrating material availability into the design process, architects and engineers can align façade system configuration with locally available reused materials. This approach not only reduces reliance on primary materials but also supports regional material cycles and reduces transportation-related environmental impacts.

The investigation revealed that reclaimed timber can be successfully incorporated into façade systems when the design accommodates variability in material dimensions and durability. Logistics, such as storage but also short transportation from the production site to the construction site, is a key element. Modular façade systems provide a suitable framework for such integration because they allow adaptation of cladding elements without affecting the structural performance of the overall system.

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REALM: A Practical Framework for Assessing Circular Economy in Modular Residential Buildings

Kenza Belkhiri[1(✉)], Viorel Ungureanu[1,2], and Raluca Buzatu[1]

[1] Politehnica University Timisoara, Timisoara, Romania
kenza.belkhiri@student.upt.ro
[2] Technical Sciences Academy of Romania, Bucharest, Romania

Abstract. The construction sector is one of the largest consumers of natural resources and generators of waste, making the transition to circular economy (CE) principles increasingly important. Modular construction systems offer significant opportunities for circularity through design adaptability, industrialized production, material reuse, and flexible configurations. However, existing CE assessment frameworks often fail to capture the specific circular potential of modular residential buildings throughout their lifecycle, particularly in relation to modular design, component reuse, and adaptability. This paper proposes a new assessment framework called REALM (Residential Modular Circular Economy Assessment and Lifecycle Management), designed to evaluate circular economy performance in modular housing. REALM integrates modular design assessment criteria, material circularity indicators and lifecycle stage evaluation within a unified analytical framework. The methodology combines design for disassembly, material flow analysis and adaptability metrics to assess circular performance from early design stages to end-of-life recovery. The framework is structured around four core components: (1) modular design assessment criteria, (2) material circularity indicators, (3) lifecycle stage evaluation covering design, use, adaptation, and deconstruction phases, and (4) operational circularity indicators, including module relocation, reuse cycles, maintenance and refurbishment. REALM treats modularity as a key enabler of circularity and proposes a structured set of indicators to support the evaluation of circular performance in modular residential buildings.

Keywords: Circular Economy · Modular Construction · Residential Buildings · Sustainability Assessment · Building Lifecycle Management

1 Introduction

The environmental impact of the construction sector has reached critical levels, accounting for around 40% of global carbon emissions, 50% of extracted materials, and 35% of total waste [1]. The European Commission Circular Economy Action Plan identifies construction as a priority sector for circular economy (CE) practices, setting ambitious targets for material recovery and waste reduction [2]. However, translating CE principles

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into practical assessment tools remains challenging, particularly for modular residential building systems. The residential sector faces specific challenges, as buildings must balance technical performance with occupant comfort, adaptability to changing family needs, and long-term affordability [3]. Traditional construction generates significant waste during construction (10% of materials) and demolition (up to 90% becomes waste) [4], with limited reuse potential. Modular construction offers advantages for circularity through standardization, prefabrication quality control, and design for disassembly [5]. Factory-based production can reduce material waste by 52% compared to on-site methods [6], while enabling material passports and end-of-life recovery strategies [7]. Despite this potential, existing frameworks do not adequately capture modular-specific circular benefits [8]. Level(s) requires extensive data and LCA expertise, creating barriers for practitioners [9].

This paper presents REALM as a CE assessment framework tailored to modular residential buildings. The framework is intended to address gaps in existing approaches by incorporating modular and residential-specific criteria, providing indicative performance thresholds, and enabling tiered assessment approach that may improve accessibility for projects with limited data or LCA expertise.

2 Background

The circular economy (CE), as defined by the Ellen MacArthur Foundation, is a systemic approach to economic development benefiting businesses, society, and the environment [10]. In the built environment, CE promotes waste elimination, keeping materials at their highest value, and regenerating natural systems [11], contrasting with the linear "take-make-dispose" model. Research shows circular construction can reduce primary material use by 80%, cut carbon emissions by 75%, and generate economic value through reuse and recovery [12]. However, achieving these outcomes requires robust lifecycle-based assessment methodologies.

Several key sustainability and circularity frameworks are reviewed below, highlighting their scope and limitations for modular residential construction:

- Level(s), developed by the European Commission, assesses sustainability across six macro-objectives, including emissions and material lifecycles. Yet, it demands extensive data, LCA expertise, and time, limiting accessibility [8, 9].
- The Ellen MacArthur Foundation Material Circularity Indicator (MCI) evaluates material flows [13] but is resource-intensive for buildings and excludes broader design and social aspects [14].
- Madaster is a digital material passport platform that registers and tracks building materials at the product and building scale, enabling material reuse and residual value assessment [15]. However, it focuses primarily on material registration rather than circular design evaluation or residential-specific performance.
- The Circular Building Indicators (CBI), developed by the Dutch Green Building Council, provide a set of quantitative indicators for assessing circular performance at the building scale [16].

Existing frameworks only partially address modular construction features, residential functional needs, practitioner accessibility, and multiple CE dimensions. REALM is proposed as a framework intended to respond to this gap (see Table 1).

Table 1. Comparison of Circular Economy Assessment Frameworks for the Built Environment.

Feature	Level(s)	MCI	Madaster	CBI	REALM
Building scale assessment	✓	–	✓	✓	✓
Material circularity	✓	✓	✓	✓	✓
Modular construction focus	–	–	–	–	✓
Design-for-disassembly	partial	–	partial	partial	✓
Adaptability assessment	partial	–	–	partial	✓
Operational circularity	–	–	–	–	✓
Lifecycle stage integration	partial	–	partial	✓	✓
Early design support	limited	–	limited	limited	✓

3 Theoretical Framework

3.1 Theoretical Framework Integration

REALM integrates three established theoretical foundations to ensure a comprehensive and credible assessment approach, as presented in Fig. 1.

Ellen MacArthur Foundation Circular Economy Principles, where REALM is grounded in the Foundation's three CE principles [10].

REALM integrates circular economy principles by reducing waste through mono-material design and design for disassembly, extending material use through durability, system independence, and residential adaptability, and supporting natural regeneration through bio-based materials and resource efficiency.

Stewart Brand's Shearing Layers: In How Buildings Learn [17], Brand describes buildings as dynamic systems composed of layers (Site, Structure, Skin, Services, Space plan, Stuff) operating at different timescales. This theory informs REALM's Building Systems Independence dimension, ensuring that faster-changing elements can be replaced without disrupting long-life components, which is an advantage particularly relevant to modular construction.

ISO 20887:2020 Design for Disassembly and Adaptability: ISO 20887:2020 defines principles such as component independence, reversible connections, material identification, and hierarchical disassembly [18]. By aligning with this standard, REALM supports end-of-life recovery, adaptability, and compliance with emerging regulatory and industry best practice.

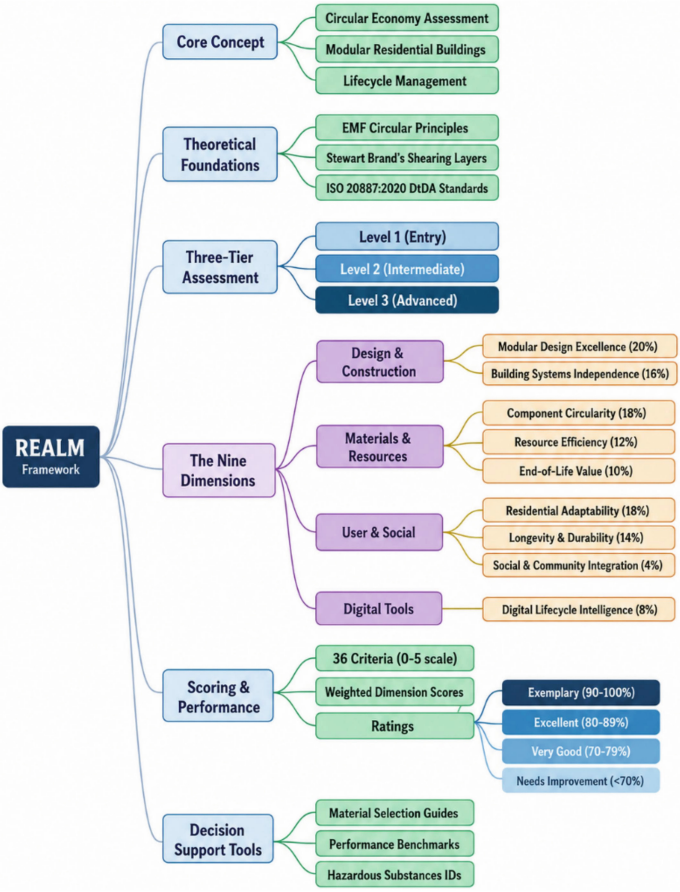


Fig. 1. REALM Framework, Dimensions, Weighting Distribution, and Scoring.

3.2 Framework Overview

REALM is structured around nine thematic dimensions, comprising 36 measurable criteria, each assessed at three requirement levels (Level 1, Level 2, and Level 3). The framework applies a weighted scoring system to generate an overall circularity index (0–100%) and is designed to be supported by decision-support tools, including material guides, performance benchmarks, and comparison tables.

Each criterion is assessed at one of three levels of increasing rigor and data requirements, aligned with the progression of project development. Level 1 corresponds to early conceptual design stages, where assessment relies on visual inspection and manufacturer declarations without requiring specialized tools or LCA expertise. Level 2 corresponds to the design development stage, where basic material inventories and simple calculations are available. Level 3 corresponds to detailed design and documentation stages, where full lifecycle assessment, lifecycle costing, and digital tools such as material passports

can be employed. Results are calculated through a weighted scoring system to generate a transparent circularity index (0–100%). Supporting tools, such as material guides and benchmarks, enhance usability from early design to post-occupancy stages.

3.3 Weight Determination Methodology

The expert panel comprised fifteen professionals from academia and industry. Dimension weights were established through structured AHP-based elicitation, informed by circularity literature and practitioner knowledge [19]. AHP is well-suited for circular economy assessment, as it enables consistent relative comparisons rather than direct weight assignment. The process followed four stages:

- *Expert Panel Formation*: An interdisciplinary panel of fifteen experts (architects, engineers, sustainability consultants, and researchers in modular construction and circular economy);
- *Pairwise Comparisons*: All nine dimensions were compared using Saaty's 1–9 scale;
- *Consistency Checking*: Logical coherence was verified using the consistency ratio (CR), with a result of 0.08 (below the 0.10 threshold), indicating acceptable reliability;
- *Weight Synthesis*: Judgments were aggregated using geometric mean and eigenvalue analysis.

The resulting weights prioritize Modular Design Excellence (20%) and Component Circularity (18%), followed by Residential Adaptability (18%), Building Systems Independence (16%), Longevity (14%), Resource Efficiency (12%), End-of-Life Value (10%), Digital Intelligence (8%), and Social Integration (4%), ensuring balanced and comprehensive circular economy coverage.

4 Demonstration Application of REALM Using the BoKlok Modular Housing System

To illustrate the applicability of the REALM framework, a demonstration assessment was conducted using the BoKlok modular housing concept as a reference case. This application is intended as an illustrative proof-of-concept rather than a full validation study. BoKlok is a residential system developed by IKEA and Skanska, based on standardized prefabricated timber modules manufactured in factory environments and assembled on site [20, 21].

The system relies heavily on off-site construction, with a large proportion of the building completed in controlled factory conditions. Prefabrication improves material efficiency, reduces construction waste, and enhances quality control compared with conventional construction methods. In addition, the modular configuration facilitates standardized components and potentially improved disassembly and material recovery at the end of the building lifecycle. These characteristics make the BoKlok (see Fig. 2) concept a suitable reference case for evaluating circular economy potential in modular residential construction.

As an example: The Modular Design Excellence dimension has a weight of 20% and includes four criteria. Based on documented characteristics of the BoKlok system,

such as standardized modular design and a high level of prefabrication, two criteria were evaluated at Level 3 and two at Level 2.



Fig. 2. BoKlok modular housing system: factory-assembled module being craned into position (left) and interior finishing in a controlled factory environment (right) [21].

These levels were converted into percentage scores (Level 1 ≈ 60%, Level 2 ≈ 75%, Level 3 ≈ 90%). The average score for the four criteria resulted in a dimension score of approximately 85%. Applying the dimension weight produced the weighted contribution: 85 × 20% = 17.0. All other dimension scores were calculated using the same evaluation and weighting procedure. The resulting values should therefore be interpreted as indicative outputs of the proposed framework, based on available documented characteristics of the reference case (Table 2).

Table 2. REALM Circular Economy Assessment Results for the BoKlok Modular Housing.

Dimension	Weight (%)	Score (%)	Weighted Result
Modular Design Excellence	20	85	17
Component Circularity	18	72	13
Residential Adaptability	18	70	12.6
Building Systems Independence	16	68	10.9
Longevity & Durability	14	75	10.5
Resource Efficiency	12	80	9.6
End-of-Life Value	10	65	6.5
Digital Lifecycle Intelligence	8	55	4.4
Social & Community Integration	4	78	3.1

Overall REALM Circularity Index: ≈ 74%, corresponding to a "Very Good" circular performance level. The results highlight strong performance in modular design and resource efficiency, while improvements could be made in digital lifecycle documentation and end-of-life recovery strategies.

5 Discussion

REALM presents several potential advantages compared with existing circular economy assessment frameworks for modular residential construction. The framework recognizes circular design elements through standardization, prefabrication, and disassembly-ready design, while fulfilling residential requirements for adaptable and permanent use. The three-tier Level 1–3 structure improves accessibility by allowing engagement according to available data, project stage, and expertise. The BoKlok demonstration illustrates practical applicability, suggesting REALM can generate understandable circularity metrics and identify improvement opportunities, particularly in digital lifecycle documentation and end-of-life recovery. However, further validation through additional case studies across different building types, climate conditions, and regulatory environments is needed, as is comparative testing against Level(s), MCI, and CBI. Although REALM is material-agnostic, benchmark calibration across steel and precast concrete systems would ensure equitable assessment. Regarding digital integration, IFC-compliant BIM models providing material specifications, connection reversibility data, and component service life estimates could enable partial automation of Level 2–3 assessments, with Digital Twin integration further supporting operational circularity monitoring.

6 Conclusion

REALM proposes a circular economy assessment framework for modular residential construction, structured around design, material, lifecycle, and operational considerations, grounded in the Ellen MacArthur Foundation principles, Stewart Brand's Shearing Layers, and ISO 20887:2020. While existing frameworks such as Level(s), MCI, and Madaster provide valuable circularity methods, they are not designed to capture modular-specific circular potential, lacking indicators for modular design, adaptability, component reuse, and operational circularity. REALM responds to these gaps through nine weighted dimensions and 36 measurable criteria across a three-tier assessment system, balancing accessibility with methodological rigor. The BoKlok application illustrates its practical use, while further comparative testing and multi-case validation remain needed to confirm robustness and usability.

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From Waste to Resilience: A Circular Adaptive Reuse Model for Post-Disaster Containers

Selman Sevindik[1(✉)], Fulya Atarer[1], Tugce Pekdogan[2], Atacan Akgün[6], Rifat Genç[3], Selimhan Sevindik[4], Caner İşler[1], Nisa Taşkın[1], Rabia Hümeyra Akdoğan[1], and Arda Ekmekci[5]

[1] Department of Architecture, Faculty of Architecture, Erciyes University, Kayseri, Turkey
selmansevindik@erciyes.edu.tr
[2] Department of Architecture, Faculty of Architecture, Adana Alparslan Türkeş Science and Technology University, Adana, Turkey
[3] Kayseri Provincial Directorate of Disaster and Emergency Management Presidency (AFAD), Kayseri, Turkey
[4] Graduate School of Natural and Applied Sciences, Erciyes University, Kayseri, Turkey
[5] Department of Architecture, İzmir Institute of Technology, İzmir, Turkey
[6] Ankara, Türkiye

Abstract. The transition to a circular economy requires reimagining waste as resource, particularly in post-disaster contexts where temporary infrastructure often becomes obsolete after its initial use. This study aims to operationalise a circular framework by repurposing nearly 215,000 container units from the 6 February 2023 earthquakes in Türkiye into affordable student dormitories. By designing a dual-use lifecycle, the research addresses the chronic shortage of university accommodation while ensuring these units remain maintained and ready for rapid deployment in potential future disasters. Using the Erciyes University campus as a case study, the methodology focuses on architectural strategies for modular retrofitting and the establishment of scalable site typologies. These designs integrate residential units with essential social and study areas, allowing for rapid implementation in diverse campus locations without requiring site-specific modification. Initial results indicate that the integration of high-standard units into permanent urban infrastructure secures the long-term economic value of the initial investment, with projections suggesting this model could yield 56.7 billion TL national savings. The research concludes that how circular strategies can transform disaster waste into resilient and permanent social infrastructure, contributing to Türkiye's 2053 net-zero emissions target.

Keywords: Circular Economy · Adaptive Reuse · Post-Disaster Housing · Student Accommodation

Atacan Akgün–Independent Researcher

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1 Introduction

The management of post-disaster recovery remains a significant challenge within the global humanitarian landscape, particularly concerning the provision of adequate shelter. Following the catastrophic earthquakes of 6 February 2023 in Türkiye, the immediate necessity for housing resulted in the rapid deployment of approximately 215,000 container units [1]. While these structures provide essential protection during the acute phase of displacement, they are frequently associated with long-term logistical and environmental burdens. Historically, temporary housing has been characterised by a linear produce-use-dispose model, often leading to the abandonment of units or their degradation into waste [2].

This linear approach is further complicated by the prolonged nature of temporary settlements, where units remain on-site far beyond their intended lifespan due to slow reconstruction and a lack of alternative housing [3]. Consequently, the substantial financial investment required for procurement and assembly is rarely recovered, as the infrastructure is treated as a single-use asset [4]. Türkiye faces a critical student housing shortage, which was further exacerbated by the earthquakes.

The research presented here is grounded in the necessity to transition towards a circular adaptive reuse model, viewing the container inventory as a valuable resource rather than a waste liability. By repurposing these surplus units into affordable student dormitories, a dual-purpose lifecycle is established to address the chronic accommodation shortage while ensuring units are maintained for future disaster redeployment. Using the Erciyes University campus as a case study, this study demonstrates how circular strategies can transform disaster waste into resilient social infrastructure, contributing to Türkiye's 2053 net-zero emissions target.

2 Post-Disaster Housing & The Circular Economy

2.1 The Post-Disaster Inventory & The Student Accommodation Gap

On 6 February 2023, two powerful earthquakes of magnitude 7.8 and 7.5 struck southern and central Türkiye, representing the most significant seismic events recorded in the country since 1939. In the immediate aftermath, the Disaster and Emergency Management Presidency (AFAD) coordinated the establishment of 414 container cities, comprising a total of 215,224 units across 13 affected provinces. Despite the unprecedented scale of this deployment, a comprehensive policy regarding the long-term utilisation or end-of-life management of these units has not been developed. Given that compliant container prices range between 200,000 and 250,000 TL, the current market value of this idle inventory is estimated at approximately 50 billion TL [5]. Maintaining these units in a state of storage while awaiting potential future disasters is anticipated to yield adverse economic and sociological consequences, as the initial capital investment remains unproductive.

Parallel to these disaster recovery challenges, the Turkish higher education sector faces a persistent accommodation crisis. Data from the Council of Higher Education (YÖK) indicate that the student population has risen to 3.7 million for the 2024–2025

academic year [6]. A 2022 report revealed that 60.4% of students were placed in institutions outside their family's city of residence [7], suggesting that over 2 million students require housing in different cities. This demographic trend has amplified the pressure on the Credit and Dormitories Institution (KYK), which serves as the primary provider of student housing. Currently, the Ministry of Youth and Sports reports a total capacity of 950,000 beds across 822 state dormitories [8]. This capacity remains considerably below the actual demand, leaving more than one million students to seek alternative, often more expensive, housing solutions.

2.2 Critical Challenges in Temporary Housing

Post-disaster housing is conceptualised as a transitional process encompassing four stages: emergency shelter, temporary shelter, temporary housing, and permanent housing. While temporary housing is intended to facilitate a return to normalcy during permanent reconstruction, the distinction between these phases is frequently blurred, as modular solutions often persist for years beyond their intended lifespan [9].

Three primary challenges exist in this context: balancing low-cost options with fully-equipped units, placing housing near destroyed dwellings to ensure resident participation, and managing high investment costs. Systematic research into these issues enhances management efficiency and accelerates recovery [10]. Furthermore, temporary housing design directly influences the transition to permanent solutions [11]. To provide comfort, these structures are often built with a durability that far exceeds their short-term purpose, remaining functional much longer than originally intended.

Spatial Allocation. . The design of temporary housing significantly influences the well-being of displaced populations by functioning as social environments that support dignity and privacy. While proximity to disaster zones is preferred, securing vacant state-owned land is often difficult. Consequently, institutions often favour remote areas due to reduced administrative complexity. However, such peripheral locations necessitate additional services and are often unsuitable for employment, potentially leading to the social isolation of relocated households. A common failure in temporary housing design is the lack of communal spaces, which can erode community ties and increase psychological distress [2]. Successful recovery is dependent on housing that fosters a sense of belonging and the restoration of social routines. Furthermore, placing temporary housing in permanent locations is identified as a critical factor in preventing the social disruptions typical of post-disaster phases.

Environmental Challenges. Environmental sustainability remains a primary concern in the deployment of temporary units. Many existing models suffer from poor thermal insulation and inadequate ventilation, resulting in internal environments that are often unsuitable for extreme climatic conditions. This lack of thermal comfort leads to increased energy consumption as residents rely on inefficient heating or cooling systems, thereby increasing the carbon footprint of the settlement. Additionally, the reliance on non-renewable or non-recyclable materials in the manufacturing process contributes to significant waste generation. The absence of an end-of-life strategy for these units often results in their abandonment, leading to land degradation and long-term environmental liabilities [4, 12].

Economic Inefficiency. The economic viability of temporary housing is frequently questioned due to the high costs associated with its short lifespan. Financial investments are required for the procurement of units, complex logistical transportation, site preparation, and eventual decommissioning, often reaching costs that are disproportionate to the quality of the housing provided. Under the traditional linear model, these costs are treated as sunk costs, as the infrastructure is rarely reused or repurposed. The lack of maintenance protocols for units further diminishes their value, making them unsuitable for redeployment in future emergencies without significant reinvestment [4, 13]. This perspective emphasizes that temporary units should not be limited to meeting immediate shelter needs; instead, their operational lifespans can be extended by integrating them into post-disaster reconstruction processes and repurposing them for alternative functions.

The circular economy transforms post-disaster housing by applying adaptive reuse, allowing structures like container units to serve productive social functions during stable periods. This dual-use lifecycle prevents units from becoming waste, ensuring continuous maintenance and rapid readiness for future emergencies. Integrating these assets into permanent urban infrastructure minimizes the environmental impact of material extraction while protecting the long-term economic value of the initial investment [14, 15].

3 Methodology & Design Criteria

To effectively manage and distribute the massive inventory of approximately 215,000 container units currently in the post-disaster stock, a highly modular and scalable design approach is essential. This methodology ensures that units can be deployed rapidly in varying configurations and expanded as demand grows or as specific site conditions evolve. By treating the container not as a static object but as a flexible building block, the system can transition between high-density clusters and smaller, more integrated arrangements without compromising social or functional standards. To demonstrate the practical viability of this modular framework, the Erciyes University campus in Kayseri has been selected as a primary case study.

The proposed design is situated within the Erciyes University campus. The site was selected to address the chronic shortage of student accommodation while utilizing existing urban infrastructure to maintain social stability. The campus offers significant strategic advantages, including designated reserve areas suitable for immediate unit placement and adjacent land availability that allows for future expansion of the housing clusters. This site-specific application serves to validate how circular adaptive reuse can transform disaster assets into a resilient, permanent part of the urban fabric. By placing the units within a permanent campus environment, the project ensures that the housing remains maintained and ready for rapid redeployment during potential future disasters.

The baseline units feature relatively high production standards, maintaining internal comfort under varying climatic conditions because of mandatory AFAD procurement specifications. The factory envelope integrates a 40 mm sandwich panel with rockwool insulation and double-glazed windows built directly into the baseline container shell. The default material configuration is sufficient with basic building energy performance

targets, helping to mitigate severe seasonal heating and cooling spikes without requiring immediate campus-side retrofitting budget.

4 The Proposed Architectural Model

The spatial configuration of the Erciyes University case study is organised to provide high-density accommodation while meeting the specific social requirements of the student population. This model repurposes 182 container units as permanent social infrastructure (Fig. 1). Within this site plan, 126 containers are allocated for student housing to alleviate the accommodation deficit in the Turkish higher education sector. A further 56 units are designated for social and service infrastructure. This allocation is intended to reduce social isolation and support the restoration of daily routines, addressing common failures in standard temporary settlements.



Fig. 1. Proposed site plan and ground floor plan designed for Erciyes University campus

A modular six-unit sub-cluster serves as the fundamental architectural component of the site. This configuration consists of a staggered vertical arrangement, with four units on the ground level and two units on the upper level. This multi-level layout provides semi-private outdoor areas and terraces, which are necessary to ensure resident privacy. To support community cohesion and logistical requirements, localised common areas are integrated for every 42 residential units. These zones include study spaces, laundry facilities, and small cafeterias, ensuring the even distribution of essential services across the various site typologies (Fig. 2).

A centralised dining hub, constructed from 30 units, functions as the primary social facility for the campus village. This central facility is intended to prevent the psychological distress and erosion of community ties often caused by a lack of communal



Fig. 2. Axonometric view of the proposed housing units

space in traditional temporary housing. The arrangement of modular sub-clusters creates sheltered, semi-private outdoor spaces between buildings that serve as quiet zones for individual study or rest. These areas are integrated with soft landscaping and green buffers to enhance the ecological quality of the site and provide a natural environment for resident well-being (Fig. 3). The integration of these units into the university's permanent infrastructure is intended to preserve the long-term economic value of the initial investment.



Fig. 3. Perspective views of the proposed housing units

The projected public financial savings (S_{nat}) are substantiated by comparing the capital expenditure of conventional dormitory construction against the adaptive reuse of the container inventory. According to official unit construction cost benchmarks [16], the standard investment for a conventional higher education dormitory is approximately 234,000 TL per student. In contrast, by allocating two students per repurposed container

unit (with an initial unit cost of 200,000 TL) the effective expenditure is reduced to 100,000 TL per student, yielding an immediate capital savings of 134,000 TL per student space. To formalize this cost avoidance across the nationwide asset base, the financial optimization model is defined in Eq. (1):

$$S_{nat} = N_{students} \times (C_{new} - C_{retro}) \quad (1)$$

Where $N_{students}$ represents the total projected housing capacity of 430,000 students (utilizing the nationwide pool of 215,000 container units), C_{new} is the conventional dormitory construction cost per student (234,000 TL), and C_{retro} is the effective container procurement/retrofitting cost per student (100,000 TL) which explicitly incorporates a baseline 15% allocation for regional logistics, site utility integration, and unit repair based on post-disaster inventory depreciation standard benchmarks. Consequently, this circular management strategy is projected to prevent a critical public expenditure, securing an estimated 57.6 billion TL in national treasury savings (S_{nat}) while simultaneously bridging the active student accommodation deficit.

5 Conclusion

This research demonstrates a systematic transition from a linear produce-use-dispose model of post-disaster housing toward a circular adaptive reuse framework. Using the Erciyes University campus as a primary case study, the paper provides a scalable architectural typology for the nationwide conversion of disaster-related assets into permanent social infrastructure. By repurposing approximately 215,000 container units from the 2023 Türkiye earthquakes into affordable student accommodation, the proposed model operationalises a dual-use lifecycle that simultaneously resolves post-disaster waste management and chronic university housing shortages. This strategy effectively transforms a significant environmental and financial liability into a resilient socio-economic asset, projected to yield nationwide public savings of 57.6 billion TL. Beyond these financial metrics, the developed architectural model prioritises thermal comfort, social well-being, and community cohesion through modular design, semi-private outdoor spaces, and integrated social facilities. Ultimately, this study offers a practical, replicable pathway for post-disaster resource efficiency, contributing directly to Türkiye's 2053 net-zero emissions targets by minimizing new material extraction and securing the long-term value of public investments.

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Towards Circular BIM by Automated Semantization of Pre-demolition Audit Data

Petr Hradil[1(✉)], Christopher Görsch[1], Robert van den Brink[1], Benjamin Lammers[2], Luise von Zimmermann[2], and Simon Duindam[3]

[1] VTT Technical Research Centre of Finland Ltd., Espoo, Finland
petr.hradil@vtt.fi
[2] Concular GmbH, Berlin, Germany
[3] Block Materials, Heerlen, Netherlands

Abstract. Having pre-demolition inspection data in a semantic structured format offers significant benefits. It enables seamless integration into Building Information Models (BIM), allowing for advanced analysis, visualization, and decision-making regarding material reuse, recycling, and deconstruction. It is the first step towards a truly circular BIM, a system capable of integrating Digital Material Passports into BIM software and allowing designers to use materials, products or even complex assemblies from the donor building in their new projects. Manually creating structured data is a complicated and time-consuming task prone to errors and inconsistencies, and therefore most of today's pre-demolition audit datasets are tabular. This paper introduces automated process of reconstruction of material and product database obtained by manual inspection of a residential building in Svalbard, Norway into a semantic representation formatted according to ISO 16739-1:2024 (IFC 4X3 ADD2). The conversion from tabular data to a standard Building Information Model requires identification and composition of the spatial context and process workflows. The inputs from the pre-demolition audit have unique material and product identifiers by Block Materials and are classified according to their reusability, recyclability, deconstructability, separability and preuse by Concular platform. The outputs will be further linked to 3D geometry obtained by Augmented Reality Mobile Mapping System combined with Li-DAR scan and additional surface features obtained by Active Hyperspectral Sensing and internal structures obtained by Ground Penetrating Radar.

Keywords: Circular Economy · Building Information Modelling · Pre-demolition Audit · Industry Foundation Classes · Digital Material Passport

1 Introduction

The construction sector generates significant demolition waste, while valuable materials remain underutilized due to fragmented documentation practices [1, 2]. Pre-demolition audits produce important data, but this information is typically stored in tabular formats without semantic structure or spatial context, limiting its reuse potential [2]. The lack of structured integration and storage of audit data into Building Information Modelling

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(BIM) environments signals a lower digital maturity than other construction processes [3] and therefore risks preventing scalable circular workflows from developing. Manual reconstruction of BIM models from spreadsheets is time-consuming, error-sensitive, and not economically viable for large-scale implementation [4].

Regulatory developments such as the Construction Products Regulation (CPR) [5] and the Ecodesign for Sustainable Products Regulation (ESPR) [6] are increasing the demand for Digital Product Passports (DPPs), requiring interoperable and machine-readable product information. BIM standards such as Industry Foundation Classes (IFC) ISO 16739 [7] provide a machine-readable, semantically rich data structure capable of representing materials, components, assemblies, and lifecycle information, offering a potential backbone for circular construction workflows. Furthermore, IFC is the default format for digital communication in the construction sector [8]. Existing research and industry platforms support material inventories, urban mining databases, and circular documentation (e.g., [9, 10]), yet they largely rely on manual modelling processes [1, 4]. Although earlier automation efforts have shown the potential of applying computer vision techniques to building documentation [2, 11], the automatic processing, transformation and storage of tabular audit data into IFC-compliant BIM models has, to the knowledge of the authors, not been researched yet.

A clear research gap therefore exists in the absence of validated, automated pipelines that convert tabular pre-demolition audit records into semantically structured BIM models capable of supporting DPP generation and interoperability. This paper addresses that gap by answering the following research question: How can tabular pre-demolition audit data be automatically transformed into an IFC-compliant BIM model that enables Digital Product Passport generation and supports circular construction workflows? To answer this question, we propose and develop an automated transformation and enrichment pipeline that reconstructs spatial context, classifies materials and components using deep learning systems for semantic mapping, and generates IFC-compliant models. The pipeline further enables the extraction of DPP-compatible datasets aligned with open JSON specifications and integrates deconstruction workflows within the IFC structure. The proposed approach is then demonstrated using a residential building case study, contributing toward circular BIM operationalization through automated semantic integration of pre-demolition audit data.

2 Classification of the Inspection Records

Building audits usually generate a bill of materials and components, providing detailed data on their quantity and quality. However, these records often lack thorough documentation of spatial configuration, location, and the relationships between materials and components within the building. Such details are essential for efficient reuse and recycling, as they help identify which items can be recovered, where they are located, and how they interact with other elements, thereby streamlining deconstruction and material selection for new projects. To overcome this gap, we apply a design science research approach [12] to develop an automated transformation and enrichment pipeline.

2.1 Basic Concept

The processing of pre-demolition audit records for further recovery and reuse of the materials and components has to ensure regulatory compliance and clarity, and therefore it should be based on the CPR [5] definition that a product is *formed, or formless physical item or a kit designed for or utilized with a purpose and placed on the market or put into service*. In this study, formed items are referred to as components, formless items as materials, and kits as assemblies. All such product shall be related to their DPPs according to the ESPR [6] and Annex V of the CPR.

The goal of our study was to generate DPP data format for products recovered from the building demolition based on the BIM and structured according to the latest version of IFC standard [7] IFC4X3 ADD2. This data format may not be fully compliant to the ESPR requirements because the relevant Delegated Acts were not yet adopted by the European Commission at the time of writing this manuscript. However, the published example of structural steel component [13] is aligned to the Technical Specification for the current harmonized product standard [14].

To generate DPP of the identified products, a full IFC transformation, enrichment and validation pipeline was developed to turn tabular pre-demolition audit data into interoperable BIM and circular-economy-ready datasets.

2.2 Unique Identifiers

One of the Building Logbooks in the Sum4RE project, Cirdax, uses a blockchain module to link materials passport to the Ethereum Blockchain and provides Universally Unique Identifiers (UUIDs) to these materials. Materials can be verified by registering the ownership of the passport in the blockchain, which also gives the possibility to see that registration as a property right at the time of registration.

The UUID blockchain registration serves as a property right that is also included in the material passport by means of its hash, i.e., the blockchain identity of the material passport. This is an essential characteristic of an UUID, as not only location, or traceability are organised in this way, it also accounts for the organisation of immutable property rights that can be used as legal framework for the reuse of materials in digital marketplaces. Therefore, the owner of the materials is always known. This enables organizing important tasks related to the circular requirements for materials, both in terms of delivery and the quality of the materials in the future. Information aspects that can get its place in the IFC-format, making it Circular BIM (or C-BIM).

2.3 Assessment of the Environmental Performance

Reusable materials have social, environmental and a financial value. The social and environmental value of materials is broader than their financial value because they also include qualitative benefits that cannot be directly recorded in monetary units. An example of these externalities is the value of saved CO_2 emissions due to the reuse of materials and components from a building because their reuse avoids the production of new materials and the environment is not further affected. Such savings can only be achieved if these materials and components can be used in an alternative way. This means that

they can be detached and separated without much damage and can once again provide a function in a real estate object with complete information for the buyer and seller.

An example of automated evaluation of reusability of building materials and components and their associated environmental impacts is provided by Concular [9]. However, without any future integration in the construction works the environmental performance of a materials is not guaranteed and most of the time of very little value. Since establishing property rights in Cirdax platform [10] also organises this kind of value, the assessment of the environmental performance can be linked to the information on that right by using UUID's as part of the general C-BIM information infrastructure,

3 Mapping the Inventory to the Building Information Model

3.1 IFC Structure

Industry Foundation Classes (IFC) are an open data model for describing built assets across their lifecycle (design, construction, operation, and decommissioning) with entities, relationships, properties, and geometry defined in a machine-interpretable way. In most cases IFC substitutes 3D geometric models of the buildings and their services that are used for visualization and collision-checking. However, geometry is only one of the aspects of the IFC semantics, and a valid model can exist without specific geometric definitions. Such model can be reconstructed from the inventory of materials and components with the option to provide geometric representation of the entities later, for instance obtained by LiDAR scanning.

The minimum functional structure of the inventory-based IFC model is illustrated in Fig. 1 where the materials are assigned to *IfcMaterial* entities, components to any subtype of *IfcBuiltElement* entity, kits to *IfcElementAssembly* entities and related external documents to *IfcDocumentInformation* entities. The recommended waste treatment and recovery from the pre-demolition audit are represented as *IfcTask* entities within the *IfcWorkSchedule.*

3.2 Automated Processing of the Tabular Data

The pre-demolition audit data obtained from the Concular and Cirdax platforms were converted into a standards-compliant IFC models using a dedicated tool developed by VTT. The tool automatically creates or enriches existing IFC models with a spatial structure (storeys, spaces), classifies building elements, materials, product types, and quantities, and generates links to the Environmental Product Declarations (EPDs), and work schedules for deconstruction and demolition. The resulting IFC is validated using both IFC schema validation and Information Delivery Specification (IDS) rules as described in the following section.

To provide a consistent IFC structure, entities defining the project, site and building are created if needed, and SI units defined. The spatial structure follows the information identified in the inventory (e.g. room and storey of the building) if available. Then the appropriate IFC entity types are identified using Large Language Model (LLM)-based classification mechanism from the free text descriptions and tabular data provided by the

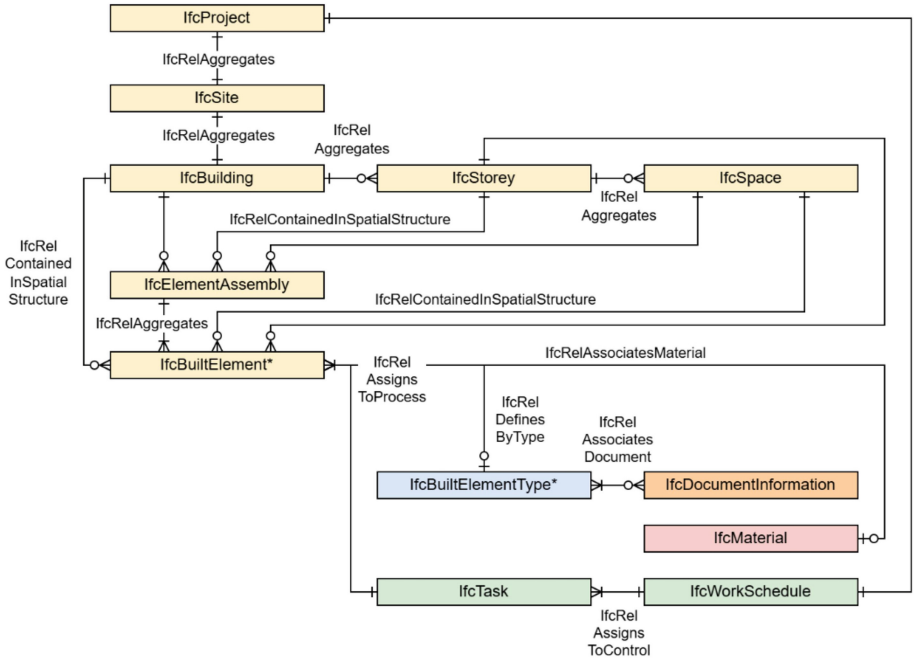


Fig. 1. IFC structure of the essential building information elements extracted from the inventory of materials and components

material audit. The used model, gemma3:27b [15] ensures that the classification can be done locally, protecting the sensitive data, and on the information provided in different languages. Since the text fields in the audit records are often repeated, the classified terms are stored in the local cache. Material definitions and building element types are updated according to the pattern pre-defined according to the JSON schema [13] for each format of the material inventory. This configuration file ensures that the specific properties of the materials and components are stored in appropriate places. For instance, the exported inventories from the Concular database were transformed according to the schema published in the GitLab project [13].

3.3 Generating IFC Work Schedule

One of the important aspects of the pre-demolition audit of the building is to identify and recommend the most environmentally efficient recovery options for the materials and components and propose further testing and measurement. Recommendations are sometimes given as scores (such as reusability or recyclability) to assist owners and contractors with future decisions for example according to the Concular methodology [16]. Based on this information it is possible to create a sequence of tasks represented as *IfcTask* elements with related entities from the inventory. The relevant information; types for such tasks are *INSPECTION*, *TESTING*, *DEMOLITION*, *DISMANTLE*, *DISPOSAL*,

and *LOGISTICS*. The tasks are generated under *IfcWorkSchedule* element assigned to the *IfcProject* as illustrated in Fig. 1.

3.4 Validation and Information Delivery Specification

The integrity of the generated IFC models is validated using the offline version of buildingSMART validation service [17] and the completeness of the information is checked using the Information Delivery Specification (IDS) standard [18].

4 Extraction of the Data for the Digital Passport

When the elements of the inventory of products and materials are integrated in the Building Information Model (BIM), it is possible to generate a digital passport for specific product (material, component or kit) with all the relevant links extracted from the BIM structure. For instance, the digital passport of the material may be linked to the component(s) where it is used, the digital passport of the component may be linked to the relevant material(s) and buildings(s) and the digital passport of the kit may be linked to the sub-component(s) and building(s). This structure is combined in our study with the existing open JSON specifications of DPPs by United Nations Economic Commission for Europe (UNECE) [19] and Material Identity [20] and illustrated in Fig. 2. The elements from Material Identity such as transaction data, test results, chemical composition, standards and validation were extended or directly imported in the schema for the compatibility reasons, while the draft UNECE schema was used as is. The examples

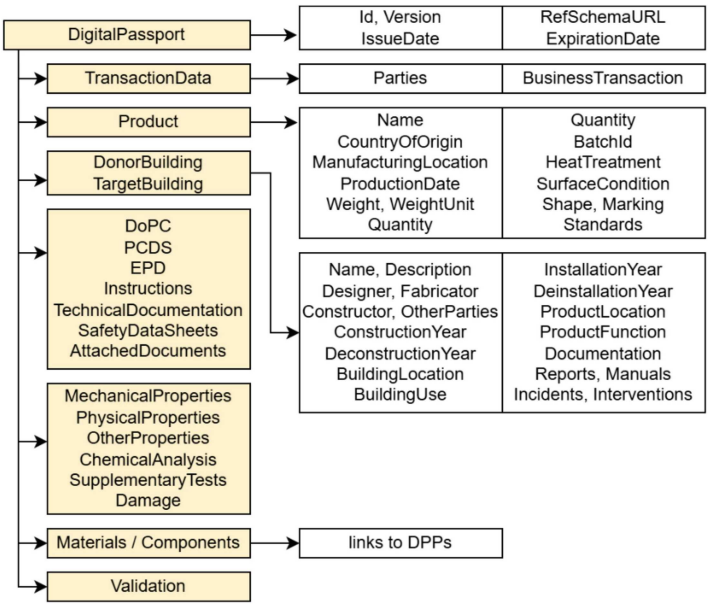


Fig. 2. Basic structure of the DPP generated from BIM according to Material Identity [20]

of generated DPP outputs are published in the GitLab workspace of the project [13]. The extraction was successfully demonstrated on several IFC models converted from Concular database, Cirdax database and created by Autodesk Revit 2026, proving compatibility with different input sources. The source files are also included in the GitLab project and open to examination.

5 Summary and Conclusions

This paper addresses the limited interoperability of pre-demolition audit data, which is typically generated and stored in tabular formats not suitable for circular construction workflows. It describes a transformation process of such data into a semantically structured, IFC–compliant BIM. The approach reconstructs the essential IFC structure by generating spatial hierarchies, classifying materials, components, and assemblies using LLM-based semantic mapping, and linking products to environmental data, documentation, and deconstruction tasks.

Audit data from Concular and Cirdax platforms are preserved through UUIDs, and their completeness is validated using IFC schema checks and IDS. The geometry-independent semantic BIM reconstruction is feasible, and the model is suitable for later enrichment using sensing technologies and extraction of elements for the new design workflows. It also reduces manual modelling effort, supports DPP generation, and provides a standards-based pathway toward a scalable C-BIM.

It should be noted that the integration and testing of Concular and Cirdax workflows is ongoing work at the time of writing this manuscript, and therefore the final examples and schema definitions published in GitLab project may slightly differ.

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Iterative Assessment of Embodied Carbon: Proposal for a System for Brazilian Residential Projects

Mayara Regina Munaro[1(✉)], Cássio Gomes de Oliveira[2], and Lucas Melchiori Pereira[3]

[1] Academic Department of Civil Construction, Universidade Tecnológica Federal do Paraná, Curitiba, Paraná, Brazil
mayaramunaro@utfpr.edu.br
[2] Polytechnic School, Universidade de São Paulo, São Paulo, Brazil
[3] Faculty of Architecture, Urbanism and Design, Universidade de São Paulo, São Paulo, Brazil

Abstract. Reducing embodied CO_2 emissions is critical for decarbonizing the construction sector, particularly in Brazil, where housing demand is high and structural systems account for a substantial share of life-cycle impacts. Yet embodied carbon assessments are typically conducted late in the project lifecycle, when major design and supplier decisions have already been defined, limiting their mitigation potential. This study investigates the conditions necessary to enable embodied CO_2 estimation in the early stages of residential building design. As the first phase of a Design Science Research approach, it combines a literature review with structured discussions involving Brazilian structural designers and specialists in cement and concrete technologies. The findings indicate that effective early-stage assessment requires incremental calculation accuracy aligned with the progressive availability of project information, explicit management of uncertainty through mitigation ranges rather than single values, and the use of transparent, regionalized emission factor inventories grounded in open data. Digital integration through interoperable Building Information Modelling (BIM) workflows is also essential to ensure traceability and automated quantity extraction. These principles informed the conceptual development of an iterative benchmarking platform designed to provide feedback during design evolution. By repositioning embodied carbon calculation as a proactive, design-integrated process, the framework enhances decision-making, risk management, and low-carbon specification in housing projects.

Keywords: Embodied carbon · Residential housing · Decarbonization · Benchmarking · Iterative Design

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1 Introduction

The built environment is responsible for more than one-third of global greenhouse gas (GHG) emissions [1]. Rapidly reducing GHG emissions from buildings is central to mitigating global climate change. To date, carbon mitigation efforts have focused primarily on the operational phase [2]; however, embodied carbon emissions from the manufacturing of construction materials already account for approximately 18% of global buildings-related emissions [1]. As advances in heating, cooling, lighting, and ventilation technologies reduce operational emissions, embodied carbon is becoming increasingly significant from a life-cycle perspective [3]. In the Global South, this proportion is often even higher, as emissions during use and maintenance phases are lower due to limited need for space heating [4]. Accordingly, leading engineers and researchers have highlighted the need for a standardized global methodology to estimate embodied carbon dioxide emissions in the building sector [3].

In Brazil, the housing deficit is estimated at nearly 8% of the total housing stock [5], while 40.8% of urban households experience some form of inadequacy [6]. This scenario will inevitably drive growth in the construction industry; however, expanding supply must be accompanied by improved performance, particularly through reductions of carbon emissions associated with construction materials. In this context, each construction technology presents trade-offs in terms of (i) embodied carbon, (ii) material costs, and (iii) sectoral innovation potential. A clear understanding of these trade-offs is essential to identify cost-effective construction solutions that minimize carbon impacts in the early stages [7].

Mitigating embodied carbon in housing requires quantifying construction materials and estimating their associated carbon footprints; however, there is limited knowledge of the embodied carbon of residential buildings in Brazil. To support consistent CO_2 mitigation policies across the housing life cycle, it is essential to establish a standardized, systematic inventory of housing carbon footprints, enabling the definition of a national baseline for Brazilian dwellings. In this context, the objective of this paper is to propose a framework that enables embodied carbon calculation in the early design stages, proposing an incremental-accuracy approach based on publicly available supply-chain data for the predominant structural materials. By anticipating embodied carbon scenarios during the design phase and presenting results as mitigation potential ranges, the proposed system aims to support informed, low-carbon decision-making in housing projects.

2 Research Design

The research adopted the Design Science Research approach comprising (1) problem understanding; (2) generation of alternatives; (3) artifact development; and (4) evaluation [8]. This paper addresses only the first stage, including a literature review, experts' discussions, and the conceptual modeling of an iterative carbon calculation system. Expert discussions and consultations with an advisory committee were conducted to validate the conceptual assumptions and align the model with current industry demands. The committee included specialists from the cement industry, design software sector, and architectural and engineering design firms. Discussions occurred iteratively as the model's

technical advancement progressed, enabling continuous assessment of its feasibility, applicability in design workflows, and alignment with carbon-reduction requirements in the construction sector.

Problem understanding was organized into sequential steps: (i) identification of research gaps and critical variables in recent literature; (ii) assessment of the technical and operational conditions required to enable carbon estimation in early design stages; and (iii) development of a logical-sequential model grounded in incremental precision and mitigation ranges as outputs. This stage concludes with the definition of an initial briefing to support the subsequent generation of artifact alternatives [8].

3 Research Gaps and Model Proposal

3.1 Diagnosis of Reactive LCA and Mitigation Potential

The calculation of embodied carbon in construction is typically carried out at a late stage, when main construction decisions have already been consolidated [9]. Under these conditions, conventional Life Cycle Assessment (LCA) primarily operates as a retrospective verification tool — valuable for diagnosing the existing situation but less effective as a decision-support mechanism during design [10]. Because it requires detailed supply chain data, results are often delivered when the potential for design changes is minimal, limiting technically significant interventions [11].

The availability of a technically robust yet strategically delayed instrument reduces mitigation potential, turning carbon assessment into a record of performance rather than a driver of design change [12]. To influence outcomes, carbon data must be available in time to inform design decisions that determine material use and supplier selection [13]. Integrating carbon estimates into the conceptual stage requires aligning calculation methods with information generated by the design team [14], particularly structural typology, material quantities, and geometric parameters. Adapting calculations to these early inputs enables influencing technical specifications and increasing mitigation potential [15].

Recent approaches propose benchmark-based strategies [16], parametric models [17], and predictive methods that estimate emissions under controlled uncertainty [18], thereby shifting LCA from a post-design specialization to a design-oriented tool [19]. Recognizing that sectoral decarbonization depends less on measurement precision than on repositioning calculations within the design process, these studies advocate agile methods with varying levels of automation compatible with collaborative digital technologies such as BIM [11]. Current discussions focus on managing uncertainty, ensuring estimates are simple and rapid enough for the design workflow, identifying which information is available at each project stage [15], and defining output that best supports mitigation efforts [20].

3.2 Level of Information Obtained in Design Projects

In Brazil, CO_2 emissions in the built environment are predominantly associated with embodied carbon, which encompasses emissions from extraction, transportation, processing, use, and end-of-life of building materials. Operational CO_2 emissions derive

from energy use during building operation, water consumption, and associated wastewater generation [21]. The analysis is restricted to CO_2, as it accounts for approximately 75% of total global warming potential and more than 90% of that of major construction materials [22].

Embodied carbon in buildings is mainly in the structure and scales with material quantities. In structural masonry housing, each m^2 of wall maps to set amounts of blocks, mortar, grout, and reinforcement steel, each with a CO_2 emission factor. Using these quantities, you can calculate $kgCO_2/m^2$ and the total emission from the wall area. This approach highlights the biggest carbon drivers and can be refined as design details become available.

3.3 CO_2 Calculation Framework in Design

Figure 1 illustrates the conceptual logic of the benchmarking system, in which successive design versions can be evaluated iteratively until user validation is achieved.

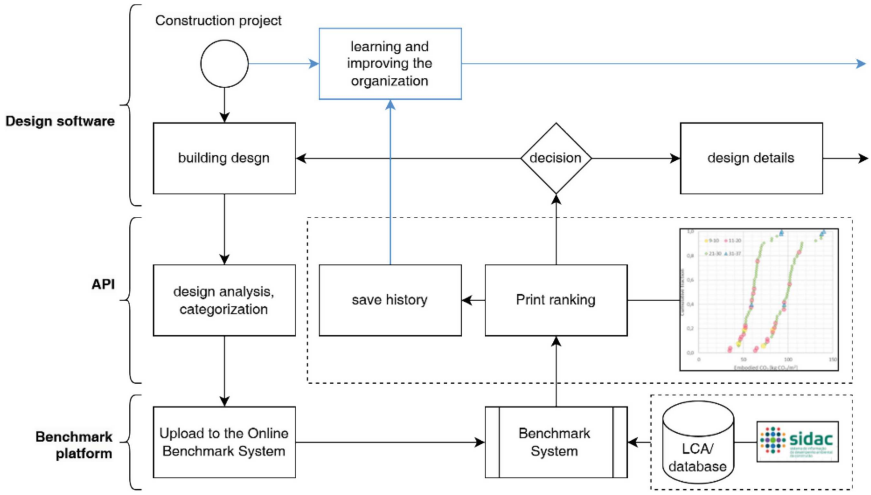


Fig. 1. Flowchart illustrating the conceptual logic of the benchmarking system.

The system calculates embodied CO_2 based on project inputs and positions the result within a ranking relative to comparable projects. Emission factors are obtained from publicly available inventories, such as the SIDAC (Information System for Environmental Performance in Construction) [23]. Continuous system use is expected to expand the project inventory and progressively refine benchmarking criteria.

3.4 Incremental Accuracy and Uncertainty Management

A single index cannot define a building's embodied carbon, as this approach tends to obscure the uncertainty arising from undefined suppliers and the lack of project detailing—issues that are often unresolved or undocumented in early design stages [24].

Likewise, it is inappropriate to require calculation through a single formula: if extensive data are demanded, the estimate can only be produced in later project phases, when opportunities for meaningful design changes are already limited; conversely, if minimal data are required, the method fails to capture and leverage the progressive increase in information that characterizes different design processes and stages [10].

Calculation accuracy should be incremental, evolving alongside project development and reducing uncertainty as information becomes available, rather than being concealed within a single aggregated value, as observed in global approaches [24]. This implies expressing results as a range representing the mitigation potential of embodied CO_2 through design, defined by minimum and maximum values. As project detailing advances and supplier-specific embodied carbon inventories become more granular, this range progressively narrows [23]. In subsequent phases—particularly those dependent on supplier selection—the interval becomes a concrete estimate of the project's mitigation potential [15].

3.5 Transparency: Empirical Grounding and Digital Integration

The reliability of embodied carbon estimates in design depends less on computational complexity than on the integrity of the informational ecosystem that supports them [23]. Sectoral diagnostics indicate that the main barriers to calculation stem from industry fragmentation, which hinders access to consistent data; the absence of clear parameters for interpreting model outputs; and the lack of verification mechanisms, particularly when data sources are not traceable—either due to limited digitalization or because results are generated by black-box models employing sophisticated algorithms, such as neural networks [25]. Transparency and trust, therefore, depend primarily on the integrity of the information ecosystem supporting the calculation [26].

Generic, synthetic, or internationalized databases—commonly embedded in design software for embodied CO_2 calculations—often overlook regional specificities, production technologies, and logistical conditions [23]. A systemic response requires publicly available, open inventories fed by primary input data and linked to supply chain origin, variability, and seasonality [23]. This empirical grounding reduces extrapolation bias and aligns calculations with actual execution conditions [20]. However, such grounding alone is insufficient without digital instrumentation supported by open modelling standards and automated quantity extraction [16]. Integrating CO_2 estimation into the design workflow depends on interoperability with CAD-BIM systems, enabling traceability between design parameters and emission factors [17].

These conditions support the structuring of a design-support system that integrates data, modelling, and verification layers. The system architecture comprises three layers: a data layer with regionalized emission factors, a modelling layer that links these factors to design parameters, and a verification layer that ensures traceability and version control. Within this framework, embodied carbon calculation becomes a verifiable technical process embedded in project development and specification.

3.6 Implications and Limitations

Anticipating embodied carbon calculations offers benefits, including greater investment predictability, as key financial commitments are often made during the early design stages of a building [13]. By explicitly acknowledging existing variability rather than concealing it, the data provide valuable input for risk management, enabling the anticipation of possible scenarios and continuous monitoring of the project's trajectory throughout the building's development and production lifecycle [23]. The system's limitations are primarily related to the automated extraction of robust project data, the lack of standardization in BIM models, and the still-limited availability of carbon emission factor data for construction materials in Brazil.

4 Conclusions

This study addressed a structural gap in the Brazilian construction sector: the lack of an information infrastructure to support embodied carbon mitigation during the early design stages of residential projects. Based on a Design Science Research approach, the study identified conditions to reposition embodied carbon assessment from a reactive verification exercise to a decision-support instrument. The findings indicate that effective early-stage mitigation depends on three core principles: incremental accuracy aligned with the progressive availability of project information; transparency based on open, regionalized, and empirically grounded emission factor inventories; and digital integration through interoperable BIM workflows ensuring traceability and automated data extraction.

Expressing results as mitigation ranges, rather than single values, allows uncertainty to be explicitly managed while maintaining relevance for design decision-making. These principles informed the conceptual development of an iterative benchmarking framework designed to provide feedback during design evolution. By embedding carbon estimation into design iterations, the proposed system enhances predictability, risk management, and the capacity to influence technical specifications. Although developed within the Brazilian housing context, the framework offers transferable insights for integrating embodied carbon mitigation into early-stage design processes in other settings.

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Circularity Assessment in the Built Environment: A Review of Policy and Practice in Light of Academic Approaches

Qiuxian Li[1(✉)], Dirk Saelens[2,3], Nuri Cihan Kayaçetin[4], Carlo Andrea Biraghi[5], Francesco Pittau[5], and Chiara Piccardo[1]

[1] Department of Civil Engineering, Building Physics and Sustainable Design Section, KU Leuven, Gebroeders De Smetstraat 1, 9000 Ghent, Belgium
rachel.li@kuleuven.be

[2] Department of Civil Engineering, Building Physics and Sustainable Design Section, KU Leuven, Kasteelpark Arenberg 40, 3001 Heverlee, Belgium

[3] EnergyVille, Thor Park 8310, 3600 Genk, Belgium

[4] Department of Interior Architecture and Environmental Design, Bilkent University, 06800 Ankara, Turkey

[5] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy

Abstract. Transitioning the built environment towards a circular economy requires standardized assessment methods to effectively measure and track circularity progress. Building upon our recently published review of academic studies, this work investigates complementary grey literature to understand how circularity is assessed by 1) analyzing existing standards, policy frameworks, Green Building Rating Systems, and specialist toolkits, and 2) conducting a comparative analysis to identify alignments and gaps between policy, practice, and academic approaches. Results show that circularity indicators primarily focus on the building level. Assessment methods vary, from quantitative approaches in standards, policy frameworks, and toolkits to semi-quantitative scoring in Green Building Rating Systems. A focus alignment is observed between grey literature and academic studies. Environmental aspects, particularly material and energy flows, and technical aspects such as design-for-disassembly receive the most attention, while social, economic, and managerial dimensions are less assessed. However, in terms of applicability, academic studies propose a more diverse set of indicators, which are often complex and difficult to apply in practice. Overall, the findings highlight fragmented methodologies for circularity assessment with varying levels of detail and inconsistent scoring approaches, which reduces comparability and hinders the development of a standardized assessment. Based on this, this study recommends future research to further refine existing methods to facilitate standardization. By synthesizing insights from policy and practice against academic studies, this study offers a basis for developing more consistent circularity assessment methods and, in turn, supporting the transition to a circular built environment.

Keywords: Circular Economy · Circularity Assessment · Built Environment · Green Building Rating Systems · Policy

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1 Introduction

The built environment represents a key sector in the transition towards a circular economy (CE) [1, 2]. Countries and regions have introduced policies and strategic frameworks to support this transition, such as the new Circular Economy Action Plan of the European Union [3] and the revised Energy Performance of Buildings Directive [4]. Despite these efforts, the effective implementation of circular strategies in the built environment requires assessment methods to measure and track circularity progress. ISO 59004:2024 defined circularity assessment as the evaluation and interpretation of results and impacts derived from a circularity measurement [2]. However, current ISO standards (e.g., ISO 59020:2024 [5]) do not specifically address circularity assessment of the built environment [6]. In the absence of standardized guidance, a variety of circularity assessment approaches has been developed. Existing research has attempted to synthesize these approaches. For example, the authors' previous work [7] conducted a systematic literature review to examine circularity assessment methods in the built environment, analyzing 66 academic studies. However, as highlighted by Khadim et al. [8], focusing solely on academic studies does not capture the full picture, as grey literature also contributes significantly to the development of existing approaches. Thus, a critical research gap remains: there is a lack of comprehensive understanding of how circularity in the built environment is assessed within grey literature, as well as a lack of comparative synthesis between these approaches and those in academic research.

To address the research gap, this work builds upon our previous review [7] of academic approaches and extends the scope to grey literature. Specifically, the work aims to: (1) identify circularity assessment methods in the built environment across building, neighborhood, city (and beyond) levels within grey literature, and (2) conduct a comparative analysis of the findings against the results of our previous review of academic literature [7] to identify alignments and gaps. By synthesizing insights from policy and practice with academic studies, this work serves as a foundation for the development of more consistent circularity assessment methods, thereby supporting the transition towards a circular built environment.

2 Methods

A review of grey literature was conducted to investigate how circularity is assessed in the built environment across building, neighborhood, and city (and beyond) scales. In this study, grey literature refers to non-peer-reviewed documents produced by governmental bodies, international organizations, industry associations, and professional initiatives. Five key categories of sources were targeted to capture both policy- and practice-oriented approaches: (1) global indicator frameworks, (2) European standards, (3) European policy-driven frameworks, (4) Green Building Rating Systems (GBRS), and (5) specialist toolkits including technical reports and project deliverables.

Only documents published in English were considered and document screening was conducted based on two main criteria: (Criterion 1) the focus on the built environment, including only documents at building, neighborhood, or city and beyond scales; and (Criterion 2) whether documents proposed indicators for circularity assessment,

either explicitly mentioned as CE assessment indicators or implicitly addressing the key resource principles of CE (e.g., close, slow, narrow, regenerate resource loops) [9, 10]. This resulted in a total of fourteen sources included in the review, which will be scrutinized in the next Section. Relevant information was extracted and organized in an Excel table, including source type, name of source, name of indicator, assessment methods, spatial scale of application, and CE dimensions and aspects addressed.

Following the analysis of grey literature, a comparative analysis was conducted against the findings of our previous systematic review of academic studies [7]. This comparison was structured around three aspects: (1) assessment method, (2) spatial scale of application, and (3) the coverage of circularity dimensions and aspects.

3 Results and Discussion

Fourteen sources were analyzed, and their respective circularity assessment indicators were collected. An overview of the reviewed sources, categorized by type, as well as the number of indicators identified in each, is provided in Table 1. The following subsections first examine the assessment methods, the circularity dimensions and aspects addressed, and the spatial scales considered. This is followed by a comparative analysis between the grey literature and academic studies.

3.1 Content Analysis

Quantitative, semi-quantitative, and qualitative methods are applied for circularity assessment across the selected grey literature. For instance, the European standards EN 15978 [13] and EN 15804 [12] include the indicator "Components for reuse," which is quantitatively assessed using Life Cycle Assessment. Semi-quantitative methods use ratings or scores to translate qualitative criteria into numerical values. The New European Bauhaus [15], for example, introduces the "Durability" indicator to measure the capacity of building to maximize the interval between refurbishments and renewals, which is scored on a scale from 0 to 100 based on a predefined scoring table. Qualitative methods consist of design criteria that are not intended to be quantified. For example, in LEED for Building Design and Construction [17], the "Planning for zero waste operations" is defined as a prerequisite that projects must meet in order to be eligible for certification, without assigning a numerical score. Compliance is instead evaluated based on specified strategies applied and documentation. Overall, quantitative methods are the most frequently applied, accounting for half of the assessment indicators identified across the reviewed grey literature. They are predominantly used in global indicator frameworks, European standards and policy-driven frameworks, and specialist toolkits. Semi-quantitative methods are also widely applied, particularly within GBRS, but are also found in European policy-driven frameworks and specialist toolkits. In contrast, qualitative methods are rarely applied and limited to GBRS, where they appear as prerequisites. Notably, in all reviewed grey literature, circularity assessment indicators are never applied individually; instead, multiple indicators are applied to capture different dimensions and aspects of circularity. For instance, the Level(s) framework [14] applied three quantitative and one semi-quantitative indicators for circularity assessment.

Table 1. Overview of analyzed sources and number of indicators.

Source category	Source	Indicator (n)
Global indicator framework	UN Sustainable Development Goals indicator framework [11]	2
European standard	EN 15804 [12] and EN 15978 [13]	4
European policy-driven framework	EU Level(s) [14]	4
	New European Bauhaus [15]	14
Green Building Rating System	BREEAM Communities [16]	5
	LEED for Building Design and Construction [17]	8
	LEED for Neighborhood Development [18]	7
	LEED for Cities and Communities [19]	9
	DGNB for Urban Districts [20]	5
	WELL [21]	2
	DGBC – Framework for Circular Buildings [22]	6
Specialist toolkits	Circular Construction in Regenerative Cities [23]	26
	ARUP Circular Building Toolkit [24]	12

A total of five circularity dimensions are covered by the reviewed grey literature, namely environmental, economic, social, technical, and managerial. Among these, the environmental dimension is the most extensively addressed, accounting for 70% of the identified indicators. Within this dimension, material efficiency represents a key aspect, which captures different stages of material flows, including inflows (e.g., use of low-impact materials), outflows (e.g., quantities of construction and demolition waste), as well as circular flows connecting them (e.g., percentage of materials for energy recovery). Energy is another frequently addressed aspect, with indicators focusing on demand-side energy efficiency and reduction, supply-side renewable energy generation, and the interaction between energy demand and supply amongst others through energy flexibility. Other environmental aspects, although less frequently covered, include water use, emissions, land use, and impacts on ecosystems and biodiversity. The technical dimension, which includes design and construction processes that enable circularity (e.g., design for adaptability, disassembly, deconstruction, longevity, and innovative construction methods), is the second most frequently addressed, covered by 18% of the identified indicators. In contrast, the economic (e.g., financial performance), social (e.g., cultural heritage conservation), and managerial (e.g., business models and innovation) dimensions receive considerably less attention.

Regarding the spatial scales of circularity assessment, most sources focus on the building level, particularly European standards and policy-driven frameworks, and specialist toolkits. Neighborhood and district scales are also considered, especially within GBRS. Larger spatial scales, such as the city and beyond, are captured by both global indicator framework and specialist toolkits, such as CIRCuLT [23]. While the majority of frameworks focus on a single scale, the LEED system offers different rating schemes that operate across different spatial scales, ranging from individual buildings to neighborhoods and cities. At the building level, indicators target improvements in the efficiency of water, energy and material use [17]. At the neighborhood level, the assessment shifts toward synergies between buildings and the shared systems that connect them, such as the indicator "District heating and cooling" [18]. At the city level, the focus expands further to include data-driven strategies, such as the indicator "Responsible sourcing for infrastructure" [19]. Overall, circularity assessment is not one-size-fits-all; the selection of indicators should be aligned with the targeted spatial scale, as the scale shapes the scope of analysis and the types of circular strategies that can be meaningfully implemented and evaluated.

3.2 Comparative Analysis

Following the analysis of how circularity is assessed in policy and practice, the results are further compared with the findings of our previous systematic review of academic studies [7] to identify alignments and gaps.

Although quantitative, semi-quantitative, and qualitative assessment methods are applied in both grey literature and academic studies, they differ significantly in how often these methods are used and the way they are carried out. Academic studies maintain a more balanced distribution across these three approaches, whereas the prevalence of quantitative and semi-quantitative methods in practice and policy suggests a focus on measurability, as shown in Fig. 1a. Semi-quantitative methods are rarely replicable in academic studies, which is largely due to a lack of consensus on indicator selection and ambiguities in scoring scales. By contrast, semi-quantitative indicators identified in grey literature, such as those within the Level(s) framework [14], the New European Bauhaus [15], and various GBRS, are developed with well-defined scoring criteria and documented with detailed methodological guidance. This transparency facilitates more consistent application, making them comparatively more replicable in practice. A similar trend is observed for qualitative methods. While an extensive number of qualitative indicators have been identified in academic studies, their practical applicability remains limited compared to those in grey literature. This suggests a clear trajectory for future research, emphasizing the further development of semi-quantitative and qualitative methods to improve their transparency and applicability in real-world contexts.

The focus on different spatial scales is consistent across policy, practice, and academic approaches, as shown in Fig. 1b. The majority of identified indicators are at the building level, while the city and beyond scales and the intermediate neighborhood level remain comparatively less-investigated. Nevertheless, recent policy suggests expanding the focus to larger spatial scales. For instance, within the policy-driven New European Bauhaus initiative [15], half of the indicators collected extend beyond the building level.

Indicators such as the "Share of renewables" are defined and assessed using scale-specific formulations, varying according to whether they are applied at the building, neighborhood, or larger urban scales. In line with this trend, future research should move beyond individual buildings, proposing scalability approaches for existing circularity indicators.

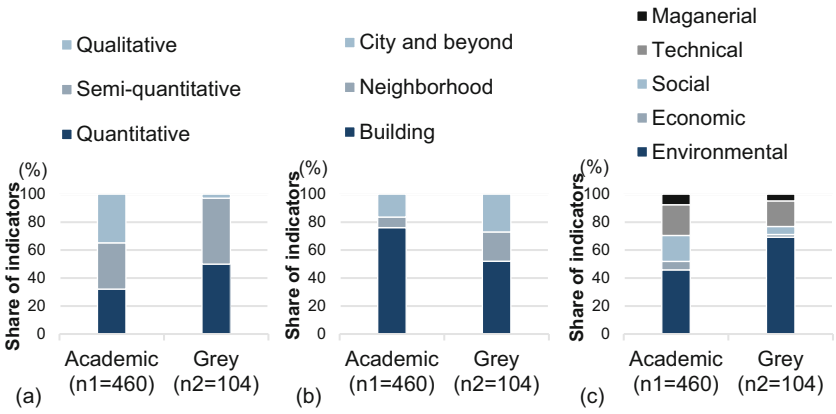


Fig. 1. Comparative analysis of indicators from academic studies and grey literature by share of: (a) assessment method, (b) application scale, and (c) circularity dimensions. n_1 and n_2 represent the total number of indicators identified in academic and grey literature sources, respectively.

Circularity assessment is recognized in both grey literature and academic studies as a multi-criteria problem, covering environmental, economic, social, technical, and managerial dimensions, as shown in Fig. 1c. While the dimensions and aspects identified in academic and grey literature are consistent, the specific methods used to assess the same dimensions or aspects still remain fragmented. For example, to assess the aspect of design for adaptability, the Level(s) framework [14] uses a semi-quantitative "Design for adaptability and renovation" indicator, while researchers tend to apply qualitative methods [7], such as the qualitative "Increased the building's future flexibility and adaptability" indicator. This methodological fragmentation suggests the need for a standardized set of indicators to ensure that circularity performance is assessed and compared consistently by researchers, practitioners, and policymakers.

4 Conclusion

This study reviewed grey literature on circularity assessment in the built environment, complementing a former systematic review of academic studies. Specifically, this included a review of standards, policy frameworks, GBRS, and specialist toolkits, and a comparative analysis to identify alignment and gaps with academic approaches.

A total of fourteen sources were reviewed, yielding 104 circularity assessment indicators that were subsequently analyzed. Results revealed considerable variation in assessment methods, including quantitative, semi-quantitative and qualitative indicators for five key circularity dimensions. While building-level assessment remains dominant in

both grey literature and academic studies, the recent policy-oriented framework suggests a growing shift toward larger spatial scales.

Methodological fragmentation indicates that future research should prioritize further refinement and alignment of existing circularity assessment methods to facilitate standardization. In particular, research should move beyond individual buildings to address larger spatial scales, such as neighborhoods and cities. Greater emphasis should also be placed on improving methodological transparency, documentation, and replicability, particularly for academic semi-quantitative and qualitative indicators, to enhance practical applicability. In this regard, indicators from grey literature may serve as useful reference examples. Finally, efforts are needed to identify and consolidate a core set of indicators that could serve as a common reference framework for researchers, practitioners, and policymakers.

A few limitations of this study can be highlighted. First, the scope of reviewed sources is largely limited to the European context. This geographical focus was chosen in line with the bibliographic analysis by Khadim et al. [8], which shows that Europe is at the forefront in this field. Although internationally recognized frameworks such as LEED [17–19] and WELL [21] were included, the primary focus on European policy initiatives and standards may limit the applicability of the findings to other regions. Second, it is possible that not all relevant grey literature was captured. Unlike academic publications, grey literature is not comprehensively indexed. As a result, some frameworks or tools may not have been identified.

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Circular Transition in Poland's Architecture

Apolonia Wozniak[1,2(✉)] and Barbara Widera[2]

[1] Doctoral School, Wrocław University of Science and Technology, 50-370 Wrocław, Poland
apolonia.wozniak@pwr.edu.pl

[2] Faculty of Architecture, Wroclaw University of Science and Technology, 50-370 Wrocław, Poland

Abstract. This article investigates the integration of sustainable and circular design principles in contemporary Polish architecture, focusing on completed buildings, projects currently under construction, and recent architectural competition proposals. The study examines 25 projects that reflect the growing national shift toward environmentally responsible construction, which include early CLT implementations (e.g., the Library in Białołęka by Ambient and the Office Building in Wiele by APA Wojciechowski) and competition-winning schemes that incorporate circular strategies (e.g., the Museum of Architecture in Wrocław by TŁO and the Academy of Fine Arts in Katowice by BDR Architects).To enable a systematic and technically robust assessment, the article introduces a dedicated evaluation framework based on 9R classification that consolidates criteria related to the design stage and the application of sustainable and circular strategies. This framework constitutes the core original contribution of the study: it operationalizes circularity assessment for architectural practice by translating broad circular-economy principles into a structured, practice-oriented analytical tool. Its formulation advances existing evaluation approaches by enabling consistent cross-case comparison and by offering a methodology that can be transferred to other national contexts undergoing similar transitions toward circular construction. The results indicate that the current level of sustainable development within the Polish construction sector is still emerging and at an early stage of development. Identified systemic limitations and underdeveloped areas include the narrow range of applied strategies and the limited number of initiatives addressing repair-related approaches. The main challenges associated with implementing circular principles in architectural practice is its predominance in public buildings and high-budget projects. The study concludes by indicating priority directions for improvement and by demonstrating how the proposed framework can support more coherent progress toward resource-efficient, low-impact architectural development in Poland and beyond.

Keywords: Circularity · Construction sector · Sustainability · Carbon footprint

1 Introduction

The European Union has established an ambitious policy framework to promote the transition toward a circular economy (CE). Strategic initiatives such as the European Green Deal [1] promote circularity, resource efficiency, and decarbonization objectives.

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The construction sector is widely recognized as a priority area due to its high levels of material consumption, waste generation, and greenhouse gas emissions across its life cycle [2]. However, progress among Member States remains uneven. Comparative assessments of CE indicators reveal significant disparities in performance across countries [3]. Moreover, the effectiveness of CE policies varies considerably between regional contexts [4].

One of the main challenges is the lack of a universally accepted CE definition, which leads to uncertainty on how circular principles can be effectively implemented within the building industry [5]. Among the identified concepts are strategies such as design for adaptability and disassembly, material recycling, prolonging the lifecycles, and broader systemic transformation [6].

One of the widely recognized frameworks for understanding circularity is based on the R-strategies, commonly associated with the reduce, reuse, and recycle [7]. For example, the 3R framework has been used to analyze challenges related to construction and demolition waste management in China [8]. In studies focusing on the adaptation of post-industrial buildings in Poland, this approach has been extended to a 4R model, with additional recovery [9]. Such frameworks enable a relatively clear and systematic interpretation of circular solutions and facilitate their comparative analysis.

Relatively few studies address manufacturing processes or spatial planning at larger scales, such as districts or cities, while the majority focus on the material scale, particularly during manufacturing and construction stages [10]. At the same time, there is an increasing need for research focusing on real-life projects [11]. Investigating such cases can contribute to a better understanding of how circular principles are applied in practice and help identify emerging best practices. Although CE concepts are widely discussed in academic literature, their practical implementation remains relatively limited [12].

To address these gaps, the study aims to evaluate the present level of circularity integration in Polish architecture. The research comparatively examines completed and planned architectural projects in Poland that incorporate circular economy principles. To ensure methodological transparency, the study employs a structured qualitative and quantitative framework that allows for cross-case evaluation.

2 Methodology

2.1 Data Sources and Inclusion Criteria

The study employed a multi-source data collection approach combining scientific literature, professional architectural publications, and publicly accessible competition records. The process was designed to ensure that the selected cases represent verifiable, documented examples of circular practices in both completed and planned buildings.

The initial identification of academic references was conducted through Scopus using the query: ("Polish" OR "Poland") AND ("circular" OR "reuse") AND ("building" OR "architecture"). This search returned 113 publications. After title, abstract, and full-text screening, 3 publications were found to contain directly relevant case descriptions, yielding 8 buildings suitable for inclusion.

Professional architectural journals were used to identify completed projects implementing circular strategies in practice. Articles published in Architektura-Murator [13]

and Sztuka-Architektury [14] were systematically reviewed. From these sources, 10 completed buildings were selected. The presence of each R-strategy was verified using the same approach for each case study. We searched for explicit evidence—such as design descriptions, implementation details, technical documentation, jury reports, or professional publications—indicating that a given strategy was intentionally applied. Only strategies supported by verifiable statements or demonstrable design features were recorded. To address the risk of incomplete or promotional information, we applied two safeguards:

– Triangulation of sources: each project was assessed using at least two independent materials whenever available
– Conservative coding: in cases where information was ambiguous, overly promotional, or insufficiently detailed, the strategy was *not* marked as present.

Third, to ensure consistency across cases, all projects were verified using the same protocol. The process was performed by two researchers, who compared interpretations and resolved discrepancies through discussion. This procedure helped maintain uniform criteria and reduce subjective bias.

To identify planned projects, public architectural competitions were reviewed using Archikonkurs [15], a platform aggregating Polish architectural competitions, and the website of Association of Polish Architects SARP [16], a frequent co-organizer. Only first-place winning entries were included, as these represent projects confirmed for construction and therefore constitute reliable indicators of future implementation. This process resulted in the selection of 7 planned buildings incorporating circular strategies. In total, 25 completed and planned buildings met the inclusion criteria and were selected for analysis.

2.2 The Circular Economy Strategies in Architecture and the Form of the Framework

For this study, the classification of circular solutions had to be systematic rather than purely descriptive, to allow the results to be translated into numerical values and a comparable indicator. To determine the scope of circular practices, a classification based on R-strategies was therefore adopted [7]. However, unlike previous studies that relied on simplified 3R or 4R frameworks [8, 9], this research applies an expanded 9R classification, enabling a more detailed differentiation. The extended 9R framework includes Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8), and Recover (R9). In architectural practice, these strategies translate into: R0 - refraining from constructing a new building or its parts when existing structures can meet the demand; R1 - designing multi-functional spaces that serve different purposes over time or introducing modularity; R2 - optimization to minimize material and energy use; R3 – adaptive reuse, reuse of materials or design for disassembly; R4 – repairing instead of replacing or designing buildings with accessible components; R5 - upgrading existing buildings to improve performance while retaining most of the structure; R6 - using building components that are disassembled and restored; R7 - Using building elements or structures for a different function; R8 – recycling materials to create new building materials; R9 - recovering energy or materials

from waste that cannot be reused or recycled. The study first identified which circular strategies were implemented in each analyzed project and then assigned a numerical value corresponding to the number of applied strategies within the 9R framework. If a project incorporated only one of these strategies, it was assigned a value of 1; if two strategies were implemented, the value was 2, and so on, up to a maximum of 10.

To estimate the stage of implementation of circular solutions in the analyzed projects, a simple scoring system termed circularity points was developed. This system considers both the number of applied 9R strategies and the project's stage of development. Each project received a score from 1 to 10 based on the number of strategies included. Additionally, weighting coefficients were introduced to reflect the stage of implementation: 0.5 for the design phase, 0.75 for the construction phase, and 1.0 for completed projects. These coefficients allow for a more balanced evaluation of projects that have not been realized and their effectiveness cannot be fully verified.

This method enables an approximate estimation of the level of circular economy implementation across the examined projects. Lower scores indicate fewer realized projects and less implemented circular strategies, whereas higher scores reflect more strategies implemented and completed in practice.

In summary, the circularity score is calculated as shown in Eq. (1).

$$\begin{aligned} &\textit{number of implemented circular strategies } (1-10) \times \textit{weighting factor} \\ &\quad \textit{based on the project stage } (0,5{-}1) \\ &\quad = \textit{circularity points } (0,5{-}10) \end{aligned} \tag{1}$$

Overall, the research framework comprises six main steps: (i) identification of circular strategies applied in each project using the 9R classification, (ii) assessment of the project stage (design, construction, or completed), (iii) quantification of the number of implemented strategies, (iv) application of a weighting factor reflecting the project stage, (v) calculation of a circularity score for each project, and (vi) evaluation of the results to determine the overall level of circular economy implementation across the sample.

3 Results

The identified cases represent a variety of functions, ranging from public buildings such as university facilities, libraries, and museums, to public spaces, to commercial buildings, including hotels and mixed-use complexes. The majority of identified cases date from the last ten years, with more examples appearing in the most recent years.

Among the analyzed buildings and designs, no project implemented more than five strategies. The most frequently adopted strategies were R3 – Reuse and R7 – Repurpose, while R9 – Recover and R4 – Repair were the least common. The mean calculated circularity points across all projects was 2.54, rising to 3.69 for completed buildings. Table 1 presents the results of the research framework

Table 1. Identified examples, including the specified project stage, listed circular strategies, and the estimated circularity points.

No.	Project name / Architekt	Year of comm. -Year of compl.	Building function	Procurement type	Project stage*	Planned / realised circular solutions **	CP ***
1	Library in Białołęka / Ambient	2022–2024	Library	Public tender	Completed (1)	R1, R3 (2)	2
2	Sprzeczna 4 / BBGK Architects	2015–2017	Residential	Private Commission	Completed (1)	R1 (1)	1
3	Towarowa 22 / JEMS Architects	2023	Mixed-use commercial buildings	Private Commission	Under development (0.75)	R3, R6, R8 (3)	2.25
4	Office building in Wiele / APA Wojciechowski	2021–2025	Office	Private Commission	Completed (1)	R1 (1)	1
5	The revitalization of the Victory Square in Gryfice / Gąska Wojcieszak PA	2025	Public Square	Architectural Competition	Design phase (0.5)	R2, R3 (2)	1
6	The development of the site of the former State Agricultural Farm (PGR) in Woźniki / Bekas T, Maculewicz A, Szczepański E	2025	Mixed-use recreational area	Architectural Competition	Design phase (0.5)	R3, R5, R7 (3)	1.5
7	Academy of Fine Arts in Katowice / BDR Architects	2025	Univeristy	Architectural Competition	Design phase (0.5)	R1, R3, R6, R8 (4)	2
8	Regional Museum in Konin / heinlewischer	2025	Museum	Architectural Competition	Design phase (0.5)	R3, R6, R8 (3)	1.5
9	Museum of Architecture in Wrocław / TŁO	2024	Museum	Architectural Competition	Design phase (0.5)	R3, R5, R6 (3)	1.5
10	CMN3 / heinlewischer	2025	University	Architectural Competition	Design phase (0.5)	R1, R3 (2)	1
11	Reclaimed-material house / mech.bud	?-2016	Residential	Private Commission	Completed (1)	R3, R7 (2)	2
12	Wrocław Brewery / SRDK Architects	2017–2024	Residential	Private Commission	Completed (1)	R2, R3, R8 (3)	3
13	“Mamut” Bakery in Wrocław / Grupa 5 Architects	2017–2022	Student Residence and Hotel	Private Commission	Completed (1)	R3, R5, R7, R8 (4)	4

(*continued*)

Table 1. (*continued*)

No.	Project name / Architekt	Year of comm. -Year of compl.	Building function	Procurement type	Project stage*	Planned / realised circular solutions **	CP ***
14	Old Coal Mine in Wałbrzych / Nizio Design International	2008–2015	the Centre for Science and Art	Architectural Competition	Completed (1)	R0, R2, R5, R7 (4)	4
15	Powiśle Power Plant in Warsaw / APA Wojciechowski, Belotto Design	2008–2021	Mixed-use commercial buildings	Private Commission	Completed (1)	R3, R7, R8 (3)	3
16	Norblin Factory in Warsaw / PRC Architects	2012–2021	Mixed-use commercial buildings	Private Commission	Completed (1)	R0, R3, R7, R8 (4)	4
17	Żnin Sugar Factory / Bulak Projekt, Bulak M, Grochowski P	2017–2020	Hotel	Private Commission	Completed (1)	R0, R2, R3, R4, R7(5)	5
18	Experimental Building in Pasłęk / WUT FoA (Górski J, Kołłątaj M, Długosz-Nowicka D, Cała I)	2005–2008	Experimental/Research	Research Project	Completed (1)	R2, R3, R6 (3)	3
19	Koszyki Market Hall / JEMS Architects	2014–2016	Mixed-use commercial buildings	Private Commission	Completed (1)	R3, R5, R7, R8 (4)	4
20	Monastery in Wrocław / Grochowski P, Szablińska-Pasik J	2017–2024	Hotel	Private Commission	Completed (1)	R0, R2, R3, R4, R7 (5)	5
21	Health Resort in Nałęczów / Bulak Projekt, Bulak M, Grochowski P	2020–2024	Hotel	Private Commission	Completed (1)	R0, R2, R3, R4, R7 (5)	5
22	Central Square in Warsaw / A-A Collective	2018–2025	Public Square	Architectural Competition	Completed (1)	R3 (1)	1
23	Faculty of Journalism, Information and Bibliology, University of Warsaw / BBGK Architects	2020	University	Architectural Competition	Under development (0.75)	R1 (1)	0.75
24	"Montownia" in Gdańsk / Rayss Group	2020–2023	Hotel	Private Commission	Completed (1)	R3, R5, R7, R8 (4)	4

(*continued*)

Table 1. (*continued*)

No.	Project name / Architekt	Year of comm. -Year of compl.	Building function	Procurement type	Project stage*	Planned / realised circular solutions **	CP ***
25	Archaeological Museum in Biskupin / Prolog	2023	Museum	Architectural Competition	Design phase (0.5)	R6, R7 (2)	1

*The weighting factor, reflecting the project stage, is shown in parentheses
** The number of R-strategies implemented is indicated in parentheses
*** Circularity points (CP) were calculated according to Eq. (1)

4 Discussion

The findings of this study provide important insight into the current state of circular economy integration in architectural practice in Poland.

4.1 Circular Economy Theory Versus Architectural Practice

The observed dominance of adaptive reuse and preservation-oriented strategies suggests that circularity in Polish architecture is currently driven primarily by resource retention rather than by fully systemic design approaches.

The limited application of repair-oriented strategies (R4) is particularly noteworthy. It suggests that architectural practice still tends to prioritize initial construction and adaptation phases, while long-term maintenance, repairability, and operational flexibility remain insufficiently integrated into design decision-making.

4.2 Fragmentation of Circular Strategies and the Absence of Systemic Design

A key observation is that none of the analyzed projects implemented more than five circular strategies simultaneously. This reinforces the conclusion that circularity is currently introduced through isolated design decisions rather than through comprehensive circular design frameworks.

4.3 Policy and Regulatory Implications

The underrepresentation of residential projects, public procurement, and lower-budget developments reveals a critical policy gap. The results suggest that existing policy instruments may not sufficiently support the integration of circular strategies beyond flagship or high-profile projects. In particular, the limited visibility of circular solutions in public tenders raises questions about how circular economy objectives are operationalized within procurement procedures.

The research framework proposed in this study directly addresses this challenge by offering a simplified yet structured indicator of circularity that could be adopted

or adapted by policy-makers. Competition organizers could require explicit material indicators, documentation of reuse potential, and evidence-based environmental strategies as part of the evaluation framework. Public clients could incorporate R-strategies into tender specifications and feasibility studies, ensuring that circular principles are considered from the outset. In this sense, the framework has clear potential to support evidence-based policy development.

4.4 The Limitations of the Study

The limitations of the method primarily stem from the characteristics of the data sources. Press releases and professional journal publications tend to highlight high-visibility projects, which may lead to the omission of work by smaller or niche architectural studios, privately funded developments, and small-scale interventions that are less frequently documented.

A further limitation relates to the reliance on publicly available information. The analysis may not capture the complete range of strategies considered, discarded, or modified during project development.

Another limitation is the equal weighting of all nine 9R strategies, although their impacts on a project are not necessarily comparable. Future research could address this limitation by introducing an additional weighting factor for the scale and overall impact of implemented circular solutions.

5 Conclusion

This study set out to evaluate the current level of circular economy integration in architectural practice in Poland through the analysis of 25 realized buildings and design proposals. The results demonstrate that, while interest in circular principles is clearly emerging, their implementation remains limited in scope, fragmented in nature, and concentrated around a narrow set of strategies—most notably adaptive reuse and the preservation of existing building resources.

The key contribution of this paper lies not only in documenting these limitations, but in how they are identified and assessed. The study introduces and applies a dedicated, practice-oriented evaluation framework that operationalizes circular economy theory for architectural analysis. By combining the identification of R-strategies with project-stage weighting and a synthetic circularity score, the method enables consistent cross-case comparison and reveals patterns that are difficult to capture through qualitative description alone.

The findings also carry important implications for policy and practice. The underrepresentation of residential development, public procurement, and lower-budget projects highlights structural barriers that cannot be addressed through design innovation alone.

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Evaluating Design for Deconstruction in Level(s): Strengths, Challenges, and Opportunities for Enhancement

Rand Askar[1,2], Christina Giarma[3(✉)], Amaryllis Iliadi Manou[3], Katerina Tsikaloudaki[3], Meri Cvetkovska[4], and Luís Bragança[1]

[1] ISISE, ARISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal
[2] ISISE, ARISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal
[3] Laboratory of Building Construction and Building Physics, Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
chgiarma@civil.auth.gr
[4] Faculty of Civil Engineering, Ss. Cyril and Methodius University in Skopje, Skopje, North Macedonia

Abstract. Circularity in the building sector is tightly connected to the recovery of materials and components for reuse and recycling, and to buildings' adaptability, facilitated by design for disassembly and deconstruction. To enable these strategies, effective deconstruction considerations must be embedded from the early design stages onwards. Accordingly, multiple circularity frameworks regard design for de-construction as essential, proposing diverse metrics and criteria for its evaluation. This study investigates how deconstruction potential is addressed within Level(s), a common European framework for assessing sustainability and circularity performance, through Indicator 2.4: Design for deconstruction. The adopted methodology is structured in five steps: (i) analysis of Indicator 2.4, including its scope, criteria/metrics, and integration into Macro Objective (MO) 2: Resource efficient and circular material life cycle; (ii) identification and synthesis of key disassembly requirements based on established frameworks; (iii) evaluation of the coverage of these requirements within Level(s); (iv) comparative assessment of methodological characteristics against selected frameworks to determine strengths and weaknesses in the Level(s) approach and highlight opportunities for alignment (v) formulation of improvement directions, including proposals for additions or modifications to different elements of the assessment. The study aims to clarify where the current approach performs well and where refinement is needed. Enhancement opportunities are detected at various levels of the framework, including refining Tier terminology, improving the inclusiveness of technical and process aspects, reconsidering criteria weights, and understanding interactions with other circularity indicators in MO2 to broaden the calculation of overall circularity score based on multiple MO2 indicators.

Keywords: Level(s) Framework · Deconstruction Potential · Design for Disassembly · Building Circularity · Performance Assessment

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1 Introduction

The transition to a circular economy (CE) in the construction sector requires integrating circular design principles from the earliest stages of planning. Circular construction promotes the prolonged use of materials, components, and systems by enabling reuse, recovery, and recycling across multiple life cycle stages, thereby preserving material value and reducing the need for new resource extraction. In this context, Design for Disassembly (DfD)—also referred to as Design for Deconstruction—emerges as a key strategy for enabling circular construction.

Since the early discussions of DfD in the 1990s [1], its principles and implementation approaches have been widely explored [2]. The international standard ISO 20887:2020 [3] "Sustainability in buildings and civil engineering works—Design for disassembly and adaptability" provides a structured framework for these principles. Numerous studies highlight the importance of embedding DfD considerations from the early design stages to maximise material recovery and overcome challenges such as information gaps, regulatory constraints, and market uncertainties that often arise later in the construction process [4]. As a result, DfD principles continue to evolve through the development of new frameworks and assessment indicators.

At the policy level, the European Union has introduced the Level(s) framework as a common methodology for assessing the sustainability of buildings throughout their life cycle [5]. Level(s) consists of six macro-objectives and sixteen performance indicators. Within this framework, Macro Objective 2 (MO2): Resource efficient and circular material life cycle focuses on circularity-related aspects of buildings. In particular, **Indicator 2.4: Design for deconstruction** aims at assessing how design decisions enable the future recovery and reuse of building materials and components.

The Level(s) framework has attracted growing research interest regarding the translation of its theoretical concepts into real-life applications and national policies. Studies applying Level(s) in pilot projects highlight both its potential and the challenges of implementation, including data availability, alignment with existing standards, and integration with digital product information systems [6]. Other research has examined its integration with green building certification schemes [7], its alignment with circularity strategies such as the 10-R Framework [8], and the implementation of adaptability requirements within Indicator 2.3 (design for adaptability) [9]. Additional work has explored its compatibility with established circularity indicators such as the Material Circularity indicator (MCI) in projects designed for dismantling [10], the use of Digital Product Passports (DPPs), to support circularity-related indicators [11].

In this context and considering that limited research has critically examined how DfD principles are operationalised within the Level(s) framework, this study addresses this gap by analysing Indicator 2.4 within the context of MO2. The study evaluates how comprehensively the indicator reflects key requirements derived from established DfD frameworks, conducts a comparative assessment with selected frameworks to identify strengths and limitations, and proposes targeted improvements to enhance the implementation of DfD within Level(s).

2 Materials and Methods

This study adopts a structured analytical approach to evaluate how Design for Deconstruction (DfD) is operationalised within the Level(s) framework, focusing on Indicator 2.4. The methodology comprises five main steps. First, Indicator 2.4 is analysed in terms of its scope, criteria, tier structure, and integration within Macro Objective 2 (MO2). Second, established DfD assessment approaches—including the Disassembly Determining Factors (DDF), ISO 20887, and the CIRLAB model—are reviewed to identify key disassembly requirements and methodological characteristics. Third, a set of core disassembly requirements is synthesised and used to assess the coverage of Indicator 2.4. Fourth, a comparative analysis is conducted to evaluate methodological aspects such as level of analysis, assessment structure, technical depth, and integration with circularity strategies. Finally, based on the identified gaps and limitations, targeted improvement directions are proposed.

3 Results and Discussion

3.1 Analysis of Indicator 2.4: Design for Deconstruction

The assessment of a building's disassembly performance is essential due to the major environmental impact of building elements and the multiple renovation cycles of different scales expected throughout a building's lifecycle. These cycles involve maintenance, repair, and replacement processes, which generate material flows that can either be recovered or lost. In this context, Indicator 2.4 aims to promote design features that facilitate future disassembly and, enhance the reuse and recycling potential of materials, components, and systems. However, disassembly remains challenged by technical, procedural, logistical and market-based barriers.

Indicator 2.4. is structured across three assessment levels, each adopting a different approach while emphasizing the involvement of project teams and stakeholders. A three-tier hierarchical classification of building elements is established throughout the indicator (Tier 1: building layers such as shell, core, and external works.; Tier 2: systems such as foundations, loadbearing structural frame, and facades; Tier 3: building elements such as piles and shallow foundations).

At Level 1 (Conceptual Design), the assessment is based on a qualitative checklist structured into three criteria (design aspects) groups. The first group (*Ease of disassembly)* addresses independence and separability of elements, as well as connection characteristics, including type, accessibility, and reversibility, and the number and complexity of disassembly steps. The second group (*Ease for reuse*) focuses on standardisation, modularity, and adaptability to future functions. The third group (*Ease for recycling*), the analysis shifts to material-level aspects, including surface treatments, homogeneity, separability, and the availability of recycling pathways.

At Level 2 (Detailed Design and Construction), the assessment becomes semi-quantitative. Evaluation occurs at Tier 3 (with optional extension to a fourth tier covering components, parts, and materials). Each element is assessed based on its best practical circularity outcome, ranging from direct reuse (coefficient 1.0) to hazardous waste (coefficient 0.0), with six intermediate options. Results are normalised by mass, with optional

value (price)-based normalisation. The resulting circularity score ranges from 0% to 100% and follows a logic comparable to the approach adopted in DGNB sustainability assessment method.

At Level 3 (As-Built and In-Use), the assessment verifies performance and the implementation of the planned design strategies by comparing the structured building with the detailed design. The same layout and templates as Level 2 are applied.

3.2 Disassembly Requirements

DfD aims to ensure that buildings and their components can be dismantled in a controlled, non-destructive manner, enabling the recovery of materials for reuse, recycling, or other circular pathways. Achieving this requires the consideration of specific technical and process-related conditions during design. These conditions, often formalised as criteria or indicators in the literature, can be collectively defined as disassembly requirements, representing the design features that enable effective deconstruction.

Among the most established approaches, the Disassembly Determining Factors (DDFs) developed by Durmisevic [2] structure the evaluation of disassembly potential through 17 parameters grouped into seven aspects: functional decomposition, lifecycle coordination, relational pattern, systematisation, assembly, geometry, and connections. These parameters are assessed using fuzzy variables (0–1) and aggregated hierarchically to evaluate three configuration indicators (transformation, independence, and exchangeability) defining the overall building's transformation capacity.

With the increasing emphasis on the CE assessment, DfD has been widely integrated into broader circularity models. Many of these approaches build on the DDFs framework and combine it with material flow indicators to form the **Building Circularity Indicator (BCI)** and its variations. Subsequent BCI developments refined the selection of DDF parameters, while later studies integrated environmental indicators (e.g., embodied carbon and energy) and adaptability metrics, expanding the scope of circularity assessment [12].

Beyond BCI-based approaches, other models further develop disassembly assessment by combining DDF principles with additional criteria. For example, the CIRLAB model [12] proposes six disassembly indicators derived from both DDF and ISO 20887, applying a decision-tree logic to guide the assessment and account for limiting conditions such as inaccessibility of components. These indicators are integrated with adaptability, resource longevity, and material flow metrics to evaluate overall building circularity.

While the DDF framework remains one of the most comprehensive approaches, many studies adopt simplified criteria focusing on key aspects such as connection reversibility, accessibility, modularity, and standardisation. Although these approaches capture core DfD principles, they often lack the detailed analysis of component relationships and assembly logic provided by DDF.

A complementary reference is ISO 20887:2020, which defines general design principles for disassembly and adaptability. The standard emphasises accessibility of components, separation of building layers, use of reversible connections, minimisation of destructive techniques, and proper identification and documentation of materials. It provides a conceptual framework supporting the integration of DfD across design and lifecycle stages.

Overall, the integration of disassembly within circularity assessment models reflects its strong interconnection with other strategies such as adaptability, modular construction, and lifecycle extension. Based on the synthesis of DDF, CIRLAB, and ISO 20887, six key disassembly requirements were identified: accessibility, connection reversibility, independence of systems, assembly logic, standardisation/modularity, and lifecycle coordination. These represent the core technical conditions enabling effective disassembly and material recovery.

3.3 Comparative Analysis

Coverage of Disassembly Requirements in Level(s). This subsection evaluates how Level(s) Indicator 2.4 addresses the key disassembly requirements identified in Section 3.2. As summarised in Table 1, the analysis examines the extent to which the indicator considers the main technical conditions that enable effective disassembly.

Table 1. Assessment of the coverage of key DfD requirements within Level(s) Indicator 2.4.

Disassembly Requirement	How Level(s) addresses it
Accessibility of elements and connections	At Level 1, accessibility of connections is explicitly addressed within the *Ease of disassembly* criteria group. The accessibility of elements is not explicitly mentioned. At Levels 2–3, these aspects are not explicitly included in the logic diagram but are implicitly relevant for circularity.
Reversibility of connections	At Level 1, reversibility and sequential reversibility of connections are explicitly addressed within the *Ease of disassembly* criteria. The same considerations should be assumed when estimating the best circularity outcome for Levels 2–3 although they are not explicitly included.
Independence / layer separation	At Level 1, independence and separability of elements are addressed under *Ease of disassembly*, while material separability is considered within the *Ease of recycling* criteria group. For Levels 2–3, separability of materials and hazardous substances is explicitly included in the logic diagram for determining the best circularity outcome, while the independence of layers is implied through the tier structure. The indicator classifies elements under systems and systems under broader groups that can be interpreted as layers (shell, core, and external works).
Assembly / disassembly logic	Sequential reversibility of connections and the number and complexity of disassembly steps are addressed within *Ease of disassembly*. These aspects are not explicitly included in the Levels 2–3 logic diagram but are implicitly relevant for determining the best circularity outcome.
Standardisation / modularity	These factors are extensively examined within the *Ease of reuse* group. Although not explicitly referenced in the Levels 2–3 logic diagram, they are expected to influence the estimation of the best circularity outcome.

(*continued*)

Table 1. (*continued*)

Disassembly Requirement	How Level(s) addresses it
Lifecycle coordination / reuse enablement	Reuse enablement is addressed across all criteria within the *Ease of reuse group* at Level 1. For Levels 2–3, reusability is further examined, including the presence and separability of hazardous substances. No explicit reference to lifecycle coordination is provided.

Comparison of Assessment Characteristics. This subsection compares the main methodological characteristics of Level(s), the DDFs framework, ISO 20887, and the CIRLAB model. As summarised in Table 2, the comparison focuses on key aspects of the assessment approaches, including the level of analysis, structure of the evaluation method, technical depth of disassembly assessment, integration with lifecycle and circularity strategies, and consideration of process and implementation aspects.

Table 2. Comparison of methodological characteristics of Level(s), DDF, ISO 20887, and CIRLAB.

Assessment Dimension	Level(s)	DDFs	ISO 20887	CIRLAB
Level of analysis	Conceptual (Level 1) and element-level (Levels 2–3), aggregated to building level	Component, assembly, and connection levels	Conceptual principles applied to components, systems, and connections (generally collective)	Component and connection level with aggregation to building level
Structure of assessment method	Qualitative checklist (Level 1); tier-based semi-quantitative scoring (Levels 2–3) using mass/value weighting and end-of-life outcomes	Fuzzy scoring with hierarchical aggregation	Principle-based guidance with optional semi-quantitative scoring (0–5, yes/no, percentages)	Composite indicator with semi-quantitative criteria using linguistic scales and score functions, normalised by component change frequency

(*continued*)

Table 2. (*continued*)

Assessment Dimension	Level(s)	DDFs	ISO 20887	CIRLAB
Technical depth of disassembly assessment	10 qualitative design aspects (Level 1); applied to end-of-life evaluation via logic diagram (Levels 2–3)	17 detailed technical parameters and relationships grouped into multiple aspects	7 conceptual design principles with recommendations for designers	6 structured indicators derived from DDF and ISO following a decision-tree logic
Lifecycle and circularity integration	Integrated within MO2 and linked to other lifecycle indicators	Limited integration with broader circularity strategies, mainly linked to adaptability	Conceptual lifecycle linkage (adaptability, durability, standardisation, modularity)	Strong integration with adaptability, longevity, material flows, and embodied impacts for energy and carbon
Process and implementation considerations	Includes documentation, planning aspects, and stakeholder roles	Limited consideration of implementation processes	Addresses safety, handling, operational considerations, and stakeholder roles across lifecycle	Moderate consideration through assessment logic and decision rules

3.4 Improvement Directions

The analysis presented in Tables 1 and 2 highlights several limitations in how Level(s) operationalises design for deconstruction. Based on these observations, several improvement directions can be identified.

First, refinement of the tier structure and terminology is needed to better reflect disassembly logic. Although the existing three-tier hierarchy provides a useful framework, relationships between building layers, systems, and elements remain implicit. A clearer alignment with layer-based design approaches and system independence principles would strengthen the assessment. In addition, a unified layer structure across all MO2 indicators should be established. For example, Indicator 2.3 refers to structure, façade, space plan, and services, while others use shell, core, and external elements. A consistent classification—starting from the bill of quantities and applied across indicators—would support coherent evaluation, enable trade-offs, and clarify each layer's contribution.

Second, the expansion and clarification of technical criteria is required. While Level 1 addresses key aspects such as reversibility, accessibility, and modularity, important requirements—such as assembly sequence logic, lifecycle coordination, and detailed component relationships—remain partially covered or implicit. Incorporating more

explicit criteria informed by frameworks such as DDF and ISO 20887 would enhance technical depth.

Third, process and implementation aspects should be more explicitly integrated. Current guidance gives limited attention to stakeholder roles and documentation. Including deconstruction planning, material passports, and digital tools (e.g., BIM and Digital Product Passports) would improve applicability across the building lifecycle.

Fourth, the assessment methodology should be refined to improve consistency. The shift from qualitative assessment at Level 1 to semi-quantitative scoring at Levels 2–3 creates discontinuities. Introducing semi-quantitative or weighted criteria at early design stages would enable more consistent and comparable results.

Finally, the integration of Indicator 2.4 within MO2 should be strengthened. Currently, Indicator 2.4 is the only MO2 indicator providing a quantified score, limiting its interaction with other circularity indicators. The development of a composite circularity index integrating all MO2 indicators would enable more balanced trade-offs (e.g., between design for adaptability and design for disassembly), support benchmarking across projects, and improve alignment with broader sustainability indicators (e.g., lifecycle impacts in MO1 and MO6). Such an approach would provide a more comprehensive evaluation of circularity and support informed decision-making.

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Building Passport-Based Circular Housing Transformation in Turkey: An Assemblage Perspective

Aysenur Babacan Demirel[1(✉)] and Candan Cinar Citak[2]

[1] Fatih Sultan Mehmet Vakif University, Yildiz Technical University, Istanbul, Turkey
ababacan@fsm.edu.tr

[2] Yildiz Technical University, Istanbul, Turkey

Abstract. Urban transformation in Turkey has accelerated through legal reforms intended to renew earthquake-vulnerable building stock. In practice, however, this process has largely been reduced to parcel-based demolition and reconstruction, shaped by fragmented decision-making, short-term profitability, and limited life-cycle thinking. This paper argues that urban transformation should be understood not only as a physical rebuilding process but also as a socio-material assemblage formed by actors, regulations, material flows, and data infrastructures. Within this framework, assemblage theory is used as a diagnostic lens and building passports are examined as informational interventions capable of reconnecting fragmented relations between actors, materials, data, and decisions. The Turkish context is characterized by fragmented datasets, weak institutional coordination, and information asymmetries that hinder adaptive reuse, material recovery, and long-term planning. In response, the paper proposes an assemblage-informed diagnostic matrix structured around four critical relations: building-data, building-component, actor-data-decision, and material-future-use. The matrix identifies where these relations are disrupted, what building passport information is required, and which circular transformation decisions this information can support. The study concludes that building passports should be understood not only as technical repositories but as governance infrastructures through which fragmented socio-material relations can be made visible and potentially reorganized.

Keywords: Building Passport · Circular Housing Transformation · Assemblage Theory · Socio-material Dynamics · Urban Regeneration

1 Introduction

Urban transformation in Turkey gained momentum after the enactment of Law No. 6306 in 2012, which aimed to renew unsafe building stock under disaster risk [1]. More recent amendments under Law No. 7471 and the establishment of the Urban Transformation Presidency further strengthened the institutional and legal framework [2]. Despite these changes, implementation has remained limited in scope. Rather than enabling comprehensive urban regeneration, transformation has often been reduced to the demolition of existing buildings and the construction of new ones on a parcel basis [2, 3].

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This prevailing model is strongly shaped by contractor-led development and short-term financial priorities [2]. Developers tend to focus on centrally located and profitable sites, while broader concerns such as infrastructure capacity, environmental performance, and long-term social impacts remain secondary [3]. As a result, conventional demolition methods are preferred, and the recovery potential of existing materials is largely ignored [4]. This pattern reproduces a linear building logic in which buildings are treated as disposable products rather than long-term resource systems.

From a sustainability perspective, this approach creates major limitations. The lack of reliable data on material composition, structural condition, and end-of-life potential prevents the integration of life-cycle thinking into urban transformation [4, 5]. Without such information, it is difficult to evaluate reuse, selective dismantling, adaptive renovation, or environmental performance. This is precisely why building passports and related digital tools have become increasingly important in recent literature: they offer a way to document buildings as material, technical, and informational entities throughout their life cycle [5, 12, 14]. However, the problem is not limited to missing technical information. Building data, material flows, regulatory requirements, and decisions are distributed among multiple actors and institutions that operate without a shared information environment. From an assemblage perspective, this fragmentation weakens the relations through which existing buildings could be evaluated as long-term material and spatial resources.

Building passports provide a potential response by making these dispersed socio-material conditions visible and accessible throughout the building life cycle [5, 12, 14]. Accordingly, this paper asks: How can an assemblage perspective inform the use of building passports to identify and address the socio-material barriers to circular housing transformation in Turkey? To answer this question, the study first interprets the current Turkish transformation model through assemblage theory and then develops an assemblage-informed diagnostic matrix linking identified disruptions to the building passport information required for circular transformation decisions.

2 Assemblage Theory, Circular Housing, and Building Passports

Assemblage theory understands social and spatial phenomena not as fixed totalities but as temporary and dynamic alignments of heterogeneous components [6]. In this view, actors, materials, rules, infrastructures, and discourses do not disappear into a single whole; they remain relatively autonomous and can be detached, reconnected, and reconfigured in new ways [6, 7]. This perspective is useful for urban transformation because it moves beyond linear explanations and highlights how urban outcomes emerge through unstable relations among multiple elements [8–10].

Applied to urban transformation, assemblage theory reframes housing as more than a physical object. A dwelling becomes a socio-material formation shaped by public institutions, private developers, property owners, legal codes, building components, financial pressures, and data systems [8, 10]. Transformation therefore involves not only physical replacement but also the reorganization of these relations (Fig. 1).

Processes such as demolition, displacement, regulatory change, and reconstruction can be interpreted as phases of deterritorialisation and reterritorialisation, through which an existing urban configuration is dissolved and a new one is stabilized [6–8].



Fig. 1. Assemblage dynamics in urban transformation: deterritorialisation and reterritorialisation.

This theoretical perspective connects closely with circular housing. Circular housing aims to extend building life, reduce virgin material use, enable repair and reuse, and maintain the value of components through design for disassembly, modularity, and life-cycle assessment [11–13, 17]. In this model, buildings are treated as dynamic material banks rather than single-use products. Such a shift, however, depends on reliable data. Without information on material origin, condition, toxicity, maintenance history, and recovery potential, circular design principles cannot be implemented effectively [12, 13].

Building passports respond to this need by functioning as structured digital repositories of building life-cycle information [14, 15]. Integrated with BIM and related digital tools, they can record material inventories, technical properties, maintenance history, environmental indicators, and end-of-life scenarios [12, 16, 18]. From an assemblage perspective, however, their relevance extends beyond data storage. Urban transformation depends on relations between buildings, materials, property owners, public institutions, contractors, regulations, and decision processes. When information is missing or inaccessible, these relations become fragmented and circular alternatives such as adaptation, selective dismantling, and reuse become difficult to evaluate. Building passports can intervene in this condition by making material and technical information traceable across actors and decision stages. In this study, assemblage theory is therefore used as a diagnostic lens, while the building passport is examined as an informational intervention capable of reconnecting fragmented relations between actors, materials, data, and decisions (Fig. 2).

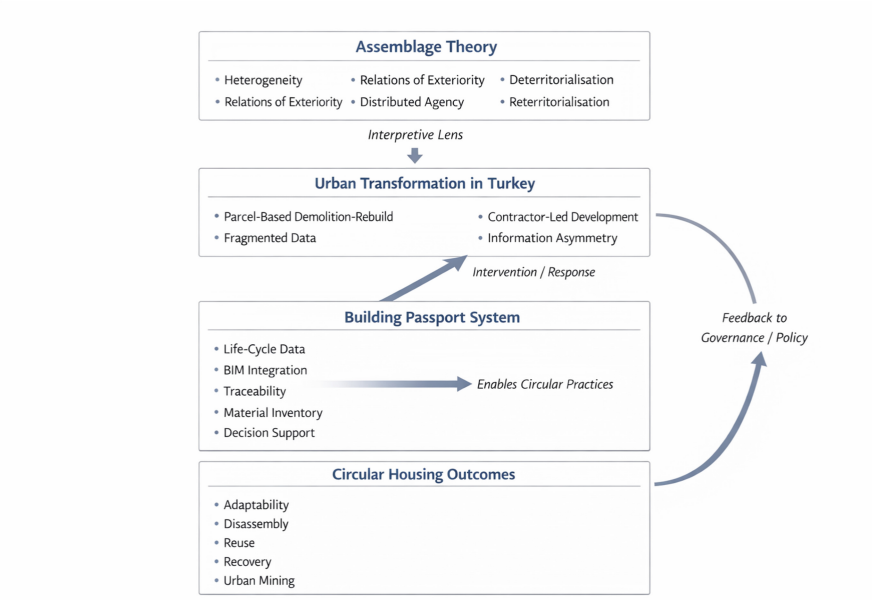


Fig. 2. Conceptual relationship between assemblage theory, circular housing, building passports, and urban transformation in Turkey.

3 The Turkish Context: Fragmented Data and Multi-Actor Decision-Making

In Turkey, one of the main obstacles to circular urban transformation is the fragmented nature of building data [1, 5]. Information about existing building stock is not gathered within a unified and continuously updated system; instead, it is dispersed across local authorities, project documents, and disconnected institutional records [1]. This fragmentation limits access to reliable knowledge about structural condition, material composition, and environmental performance [5].

The problem is intensified by the multi-actor nature of urban transformation. Central government, municipalities, contractors, consultants, demolition firms, and property owners all participate in the process, but they do not operate through a shared data environment [2, 19, 20]. As a result, decision-making is characterized by information asymmetry, coordination problems, and unequal access to technical knowledge [19] (Fig. 3).

Under these conditions, short-term economic logic tends to dominate, while long-term environmental performance and reuse potential remain poorly integrated into practice [4, 5].

This is why building passport systems are particularly relevant in the Turkish context. By centralizing life-cycle data and making it accessible to multiple stakeholders, they can reduce uncertainty and support more transparent decision-making [14, 16, 20]. They also create the informational basis required for selective demolition, repair, adaptation,

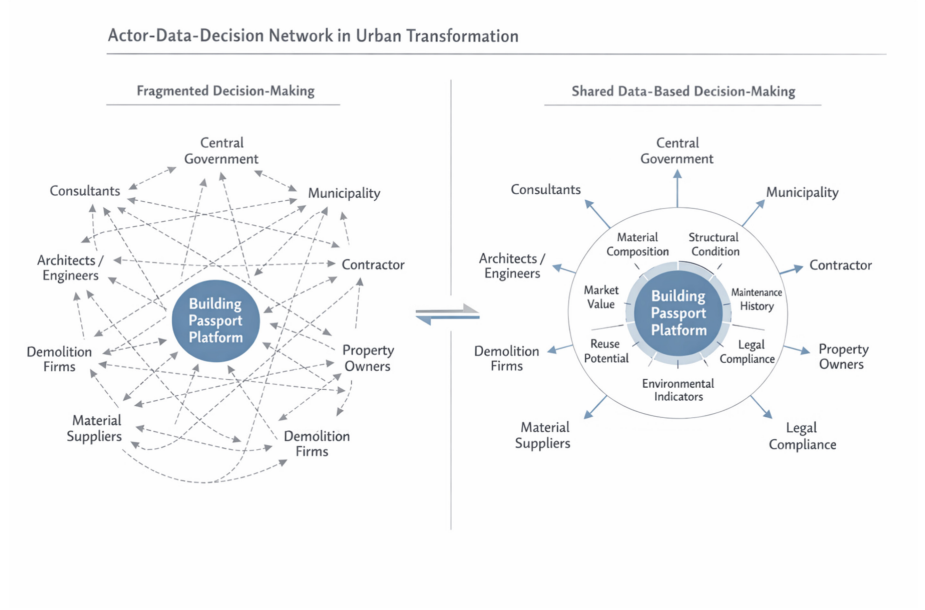


Fig. 3. Fragmented versus shared data flows among stakeholders in urban transformation.

and material recovery, all of which are essential for a circular transformation model [12, 17, 18].

Viewed through this framework, the Turkish case can be understood as a fragmented urban transformation assemblage. The central problem is not the absence of individual actors, regulations, or technical knowledge, but the weak connections between them. Material information is disconnected from demolition decisions, building performance data from redevelopment choices, and stakeholders from a common decision environment. These disruptions limit the capacity of the existing building stock to be evaluated for adaptation, reuse, selective dismantling, or material recovery.

The following section therefore translates these assemblage-level disruptions into a diagnostic matrix. Rather than scoring buildings, the matrix asks where a critical socio-material relation is disrupted, what information is missing, and what building passport information could support a circular transformation decision.

4 Results: An Assemblage-Informed Building Passport Diagnostic Matrix

To operationalize the theoretical argument, the study proposes an assemblage-informed diagnostic matrix for circular housing transformation in Turkey. The matrix does not evaluate circularity through a numerical score. Instead, it identifies critical disruptions between the actors, materials, information, and decisions that constitute the urban transformation assemblage and connects these disruptions with the information that a building passport should provide.

The matrix was developed through a conceptual synthesis of the two bodies of literature discussed in the previous sections. Building passport studies were reviewed to identify recurring information requirements, including material inventories, structural and maintenance records, life-cycle indicators, traceability, adaptability, disassembly, and recovery potential [12, 14–18, 21, 22]. These information requirements were interpreted through assemblage concepts concerning heterogeneous actors and material components, relations of exteriority, and processes of deterritorialisation and reterritorialisation [6–10]. The resulting matrix connects four recurrent problems identified in the Turkish context—fragmented building information, irreversible physical configurations, fragmented actor-decision relations, and disconnected material flows—to corresponding building passport information and circular transformation decisions [1–5, 19, 20]. Assemblage theory identifies the relations that constitute the urban transformation process; the matrix diagnoses where these relations are disrupted; and the building passport defines the information required to reconnect them (Table 1).

Table 1. Assemblage-informed building passport diagnostic matrix for circular urban transformation

Assemblage relation	Identified disruption	Building passport information required	Supported transformation decision
Building-data relation	Material, structural, maintenance, and environmental information is incomplete or dispersed across different records.	Material inventory; structural condition; maintenance history; LCA indicators; component traceability.	Determines whether adaptation, renovation, selective dismantling, or replacement can be evaluated on reliable evidence.
Building-component relation	Components and connections may prevent adaptation or non-destructive dismantling.	Component type; connection method; modularity; adaptability; disassembly and deconstructability information.	Identifies whether components can remain in use, be adapted, dismantled, or directly reused.
Actor-data-decision relation	Stakeholders operate with unequal access to information and decisions are poorly traceable across the transformation process.	Data ownership and accessibility; stakeholder access; decision records; communication protocols; shared platform information.	Creates a common information basis for negotiation and makes transformation decisions more transparent and traceable.
Material-future-use relation	Demolition decisions are disconnected from information about recovery, reuse, and secondary material flows.	Reuse/recycling potential; recovery quantity; component condition; second-hand value; selective dismantling requirements.	Connects pre-demolition decisions with reuse, recovery, urban mining, and secondary material markets.

The matrix changes the role of the building passport from a passive repository of building information into a diagnostic decision-support infrastructure. Each row begins with a relation within the urban transformation assemblage and identifies what prevents that relation from supporting circular transformation. The corresponding passport information then provides the informational basis required to reconsider the transformation decision.

For example, before the redevelopment of an apartment building, missing material and structural information would first appear as a disruption in the building-data relation. The passport would indicate the need for additional survey and documentation before demolition or renovation is selected. If information exists but components cannot be separated without destructive loss, the problem shifts to the building-component relation. Similarly, if reusable components are identified but this information does not reach demolition firms or potential secondary users, the material-future-use relation remains disrupted.

From an assemblage perspective, these distinctions are important because circular transformation cannot be achieved by accumulating building data alone. What matters is whether information changes the relations through which actors evaluate buildings and materials. The matrix therefore identifies where intervention is required before the existing assemblage is replaced through conventional demolition and indicates how building passport information can support its reconfiguration toward adaptation, reuse, recovery, and more informed redevelopment.

5 Discussion and Conclusion

This study asked how an assemblage perspective can inform the use of building passports to identify and address socio-material barriers to circular housing transformation in Turkey. The analysis shows that the central problem is not simply a lack of building information. Rather, the current transformation model is characterized by fragmented relations between building data, material components, actors, and decisions. Under these conditions, demolition and reconstruction become the dominant response because alternative futures for existing buildings and materials remain difficult to identify and coordinate.

Assemblage theory changes how this problem is understood. Instead of treating the building as an isolated physical object, it directs attention to the relations through which its future is decided. Material condition, regulatory requirements, ownership, technical knowledge, economic priorities, demolition practices, and available data operate together as a socio-material configuration. Circular transformation therefore requires intervention not only in the physical building but also in these relations.

The building passport provides such an intervention by creating a shared informational layer between the building, its components, stakeholders, and future material flows. The proposed matrix operationalizes this argument by identifying four critical relations: building-data, building-component, actor-data-decision, and material-future-use relations. For each relation, it identifies a potential disruption, the building passport information needed to make that disruption visible, and the transformation decision that this information can support.

The contribution of the matrix is therefore diagnostic rather than predictive. It does not calculate a circularity score or prescribe a single transformation outcome. Instead, it provides a structured way to ask what is currently disconnected before a decision to renovate, dismantle, recover, or replace a building is made. In this sense, the building passport becomes more than a digital repository: it becomes an infrastructure through which fragmented socio-material relations can be made visible and potentially reorganized.

For the Turkish context, this reframes circular urban transformation from a question of what information should be stored to a question of what relations that information should enable. Future empirical studies can test the proposed matrix through building-scale cases and stakeholder applications and examine whether these informational connections alter actual renovation, demolition, and material-recovery decisions. The conceptual contribution of this study is to establish this missing link between assemblage theory and building passport implementation, positioning data as an active component in the reconfiguration of urban transformation toward more circular outcomes.

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Design for Disassembly Performance of Inter-Modular Connections in Modular Steel Buildings

Farhan Ahmed, Michaela Gkantou(✉), and Ana Bras

BEST Research Institute, School of Engineering and Built Environment, Liverpool John Moores University, Liverpool, UK
m.gkantou@ljmu.ac.uk

Abstract. Design for Disassembly (DfD) is a fundamental enabler of circularity in modular steel buildings (MSBs), as the long-term reuse of modules depends directly on the reversibility and mechanical separability of inter-modular connections (IMCs). This paper presents a comparative technical assessment of four primary IMC typologies—bolted, post-tensioned tie-rod, self-locking, and grouted systems. Relevant international standards are reviewed to identify requirements governing reversible assembly, structural integrity during repeated cycles, and material traceability. Using a Multi-Criteria Decision-Making (MCDM) framework, each connection type is evaluated across five performance vectors: operational accessibility, modular independence, reversibility, structural integrity, and post-disassembly recertification. Quantitative analysis shows that bolted connections achieve the highest DfD Performance Index (PI) at 91%, offering high demountability despite susceptibility to slip. Post-tensioned tie-rod systems follow with a PI of 87%, providing rigid behaviour, but requiring specialised hydraulic equipment for safe release. Self-locking mechanisms attain an average PI of 80%, constrained by limited visibility of internal elements. Grouted connections score the lowest PI at 40%; although they can provide full-strength capacity, their permanent bonding necessitates destructive removal. Overall, the study demonstrates that circularity in MSBs is governed by a trade-off between structural performance and disassemblable integrity, with bolted and post-tensioned tie-rod systems identified as the most effective solutions for achieving reversible, multi-cycle modular construction.

Keywords: Design for Disassembly (DfD) · Modular Steel Buildings (MSBs) · Reversible Connections · Circular Construction · Inter-modular connections (IMC) · Material Passports

1 Introduction and Relevant DfD Standards

The construction industry is shifting toward environmentally driven, resource-efficient practices. Modular steel buildings (MSBs) [1] offer rapid, high-quality solutions for applications, such as disaster response and fast-track healthcare [2], but sustaining long-term value requires reuse pathways that enable component recovery and multi-cycle

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deployment. Deconstruction, the selective disassembly of building components is central to circular-economy practice because it preserves structural integrity and supports repeated reuse [3].

In MSBs, reversibility depends on inter-modular connections (IMCs), making Design for Disassembly (DfD) the key framework governing separability, accessibility, and damage-free extraction. Reversible systems also require coordinated disassembly planning, traceable material data, and value-retention processes. Building Information Modelling (BIM) supports this by embedding material and connection metadata for disassembly simulation and reuse assessment [4]. While traditional codes emphasise safety and structural performance, construction standards increasingly mandate reversibility, traceability, and controlled dismantling, criteria critical for certifying IMCs across multiple life cycles. Table 1 summarises the main standards for reusable IMC design.

Table 1. Relevant DfD standards and codes.

Standard	Scope & Technical Relevance	IMC Specific Justification
ISO 20887 [5]	Requirements for reversible and accessible joints, and disassembly sequencing.	Establishes principles for non-destructive, demountable joints to facilitate modular recovery.
BS EN 15978 [6]	Defines life-cycle assessment modules (A–D).	Essential for evaluating end of life and reuse benefits for recovered joints.
BS EN 15804 [7]	Product-level EPD rules for circularity and reuse potential.	Standardises recoverability claims for MSBs and their constituent fasteners.
EN 1993-1-8 [8]	Eurocode 3 provisions for steel joints.	Governs mechanical behaviour and replaceability of bolted IMCs.
PAS 2080 [9]	Carbon management through value-chain collaboration.	Prioritises low-carbon procurement of reversible assemblies.
IStructE Ltd. [10]	Guidance on structural steel reuse, testing, and re-certification.	Provides protocols for validating the residual capacity of IMC bolts and plates after service.
BS EN 18239 [11]	Digital passports to trace structural properties.	Enables BIM-integrated tracking for verified reuse of modules.

To systematically compare the circularity potential of MSBs, this study applies a Multi-Criteria Decision-Making framework (MCDM) to assess the DfD characteristics of four IMC typologies, bolted, tie-rod, self-locking, and grouted systems. A Disassembly Performance Index (PI) is then calculated to determine which IMCs are most suitable for reversible, multi-cycle MSB reuse.

2 Methodology of DfD Assessment

MCDM approach is used to systematically evaluate circularity [12]. This method enables qualitative and semi-quantitative judgments to be normalised and aggregated into a single quantitative PI, using Eq. (1):

$$PI_J = \left(\sum_{i=1}^{n} w_i r_{ij} \right) \times 100\ (\%) \tag{1}$$

where: w_i = weighting factor ($\Sigma w_i = 1$); rating $r_{ij} = s_{ij}/S_{max}$; s_{ij} = Likert score (1–5) for joint j at criterion i; $S_{max} = 5$; and n = total criteria (n = 5).

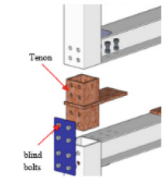
IMCs are assessed using a five-point Likert scale (C1–C5). The qualitative benchmarks and scoring logic that underpin these ratings are presented in Table 2. The assigned scores are based on qualitative interpretation of reported IMC behaviour and disassembly characteristics from the reviewed literature. Scores are derived using expert judgement to ensure consistency across IMCs. Although the MCDM framework enables systematic comparison, the semi-quantitative scoring process involves expert judgement and some inherent subjectivity.

Table 2. DfD performance scoring matrix for IMCs.

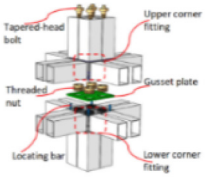
Category	Criterion	Objective	1	2	3	4	5
A: OE (30%)	C1: Accessibility	Ease to dismantle	Destructive removal	Heavy machinery	Light power tools	Two-sided, tools	One sided, tools
	C2: Disassembly sequence	Module decoupling	Partial demolition	High-interlocked	Moderate-needs bracing	Reverse order	Fully independent
B: SC (50%)	C3: Reversibility	Damage to IMC mechanism	Permanent joint	Partially destructive	Semi-reversible	Sacrificial bolts	Fully mechanical
	C4: Damage decoupling	Severity of joint deformation	Failure of primary member	Major deformation	Minor local yielding	Needs replaceable parts	Sacrificial fasteners
C: PDV (20%)	C5: Recertification index	Ease of reuse inspection	Non-rectifiable	Hidden parts	Partial access	Minor wears	NDT ready

3 Performance of IMC Typologies

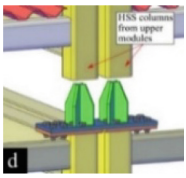
IMCs, identified from the literature and illustrated in Fig. 1, are evaluated using the proposed MCDM framework. Weighting factors assign priority to structural circularity (SC) (50%), operational efficiency (OE) (30%) and post-disassembly viability (PDV) (20%) to reflect the emphasis on non-destructive recovery and reliable recertification. Greater weighting is assigned to SC because irreversible damage to primary members directly limits multi-cycle reuse potential, while OE and PDV govern the practicality of dismantling and reuse verification. Table 3 presents the resulting scores and corresponding PI values.



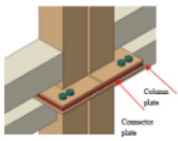
(a) (Full strength) Bolted [13]



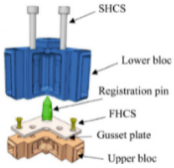
(b) Bolted [14]



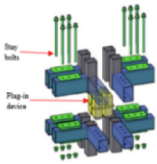
(c) (Pin-jointed) Bolted [15]



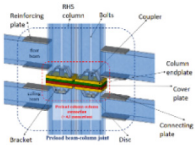
(d) (Full strength) Bolted [16]



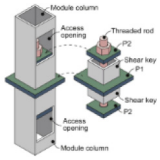
(e) Bolted [17]



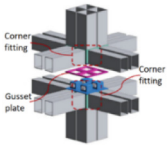
(f) (Pin-jointed) Bolted [18]



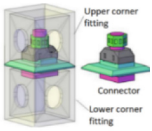
(g) (Rigid) Tie-rod [19]



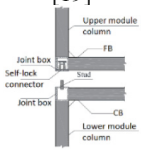
(h) (Semi-rigid) Tie-rod [20]



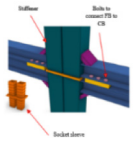
(i) (Full-strength & semi-rigid) Self-locking [21]



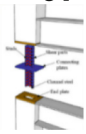
(j) (Semi-rigid) Self-locking [22]



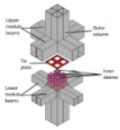
(k) (Full-strength & semi-rigid) Self-locking [23]



(l) (Full-strength & semi-rigid) Grouted [24]



(m) Grouted [25]



(n) (Partial-strength) Grouted [26]

Fig. 1. Schematic representation of studied IMCs.

Table 3. DfD scoring for IMCs.

IMC	C1	C2	C3	C4	C5	PI	Remarks
Criteria	*15%*	*15%*	*25%*	*25%*	*20%*	100%	
[13] Bolted Fig. 1a	*4*	*5*	5	5	3	89%	C1: Uses two-sided friction bolts in beams and one-sided blind bolts; C2: Independent; C3: No site-welds; C4: Damage-free separation; C5: Diaphragm-limited non-destructive testing (NDT).

(*continued*)

Table 3. (*continued*)

IMC	C1	C2	C3	C4	C5	PI	Remarks
[14] Bolted Fig. 1b	5	5	5	5	2	88%	C1: One-sided access; C2: Independent; C3: Bolts remain undamaged; C4: Tapered-head interface (damage free); C5: Obscured (invasive NDT).
[15] Bolted Fig. 1c	5	5	5	5	3	92%	C1: No internal bolts; C2: Independent; C3: Fully mechanical; C4: Non-destructive disassembly; C5: Cruciform components need specialized inspection.
[16] Bolted Fig. 1d	4	5	5	5	5	97%	C1: Requires access to both sides; C2: Independent; C3: Bolts remained undamaged; C4: Non-destructive disassembly; C5: Direct inspection.
[17] Bolted Fig. 1e	4	5	5	5	3	89%	C1: Two-sided access required; C2: Independent module lifting; C3: Reversible; C4: Integrity is preserved; C5: Blocs require specialized inspection.
[18] Bolted Fig. 1f	4	5	5	5	4	93%	C1: Access required for bolts; C2: Independent; C3: Fully mechanical; C4: No damage to main members; C5: Coating removal from plug-in.
[19] Tie-rod Fig. 1g	5	5	5	5	2	88%	C1: One-sided access; C2: Independent; C3: Reversible rod bolt; C4: Rod and column integrity is preserved; C5: Rod and coupler are obscured inside column.

(*continued*)

Table 3. (*continued*)

IMC	C1	C2	C3	C4	C5	PI	Remarks
[20] Tie-rod Fig. 1h	3	5	5	5	3	86%	C1: Requires a hydraulic jack; C2: Independent; C3: Fully reversible by unloading tie-rod; C4: Entirely non-destructive; C5: Welded plate interfaces require detailed inspection.
[21] Self-locking Fig. 1i	3	5	5	3	3	76%	C1: Need access holes in columns to retract spring-tabs; C2: Independent; C3: Reversible; C4: Access holes necessitate retrofitting; C5: Limited access to inspect locking components of corner fittings.
[22] Self-locking Fig. 1j	5	5	5	5	3	92%	C1: One-sided internal access; C2: Independent; C3: Rotary bolt removal restores joint to fully pre-assembled state; C4: Entirely non-destructive; C5: Limited access to inspect locking components of connector, requiring detailed verification.
[23] Self-locking Fig. 1k	3	5	5	4	1	73%	C1: Need drilling access holes in joint boxes to retract spring-latches; C2: Independent; C3: Reversible; C4: Damage is confined to joint box. Primary elements integrity is preserved; C5: Non-rectifiable.
[24] Grouted Fig. 1l	2	5	1	2	1	40%	C1: Requires machinery to dismantle grout; C2: Independent; C3: Non-reversible; C4: Grout removal requires cutting the column-ends and subsequent repairs for reuse; C5: Non-rectifiable.

(*continued*)

Table 3. (*continued*)

IMC	C1	C2	C3	C4	C5	PI	Remarks
[25] Grouted Fig. 1m	2	5	1	2	1	40%	C1: Requires machinery; C2: Independent; C3: Non-reversible; C4: Grout removal requires column-ends repairs for reuse; C5: Non-rectifiable.
[26] Grouted Fig. 1n	2	5	1	2	1	40%	C1: Requires machinery; C2: Independent; C3: Non-reversible; C4: Grout removal requires column-ends repairs for reuse; C5: Non-rectifiable.

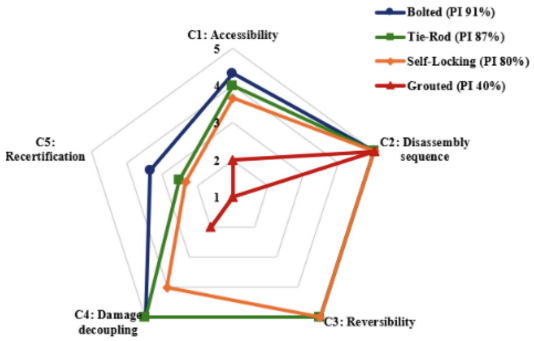


Fig. 2. Comparative PI of IMC Typologies

Quantitative results in Fig. 2 reveal performance based on connection typologies.

- *Bolted Connections (PI = 91%):* These achieve the highest PI, as damage is isolated to replaceable fasteners while the main structural components remain intact. Their full mechanical reversibility supports multi-cycle reuse. However, structural efficiency may be reduced by bolt-hole clearances and the associated risk of slip-controlled behaviour.
- *Tie-Rod Connections (PI = 87%):* Tie-rod systems score highly in reversibility but face circularity constraints due to their reliance on specialised hydraulic jacks for tension release and the difficulty of inspecting concealed internal components during recertification.
- *Self-Locking Connections (PI = 80%):* These mechanisms embed the locking interface within the joint, limiting visibility and requiring invasive intervention for safe retraction. This reduces operational efficiency during deconstruction. Additionally, their dependence on tight manufacturing tolerances may constrain geometric flexibility and affect structural performance.

- *Grouted Connections (PI = 40%):* Although grout can provide rigid, full-strength behaviour, its strong bonded interface prevents non-destructive removal. Deconstruction typically results in section loss at column ends, requiring substantial refurbishment prior to any potential reuse.

4 Conclusions

This study demonstrates that the disassembly performance of modular steel buildings is governed primarily by the reversibility and inspection accessibility of their inter-modular connections. Using an MCDM-based DfD assessment, bolted and tie-rod systems emerged as the most suitable typologies for multi-cycle reuse, offering high mechanical recoverability and manageable recertification demands. Self-locking mechanisms provide moderate performance, limited by obscured interfaces and precision-dependent manufacturing, while grouted connections remain incompatible with circularity due to their inherent destructiveness. Overall, the results highlight that circular MSBs require reversible and accessible connection systems that enable robust dismantling and reuse. Future work could include quantitative environmental indicators and life cycle assessments to strengthen the framework's practical applicability.

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Building Designers' Attitudes Towards Reuse of Materials in Construction

Joana Gonçalves, John van Oorschot(✉), Steven Claes, and Michiel Ritzen

Vlaamse Instelling voor Technologische Onderzoek (VITO)/EnergyVille, Boeretang 200, 2400 Mol, Belgium

john.vanoorschot@vito.be

Abstract. The construction sector's contribution to environmental degradation and global waste highlights the need for circular practices that extend the life of existing resources. By prioritizing reuse, adaptability, and longer service life over demolition and replacement, circular construction can reduce primary material extraction and construction waste across scales of the built environment. Yet its uptake depends not only on technical solutions but also on the values, emotions, and tacit knowledge guiding designers' decisions. This study examines how these determinants of behavior shape building designers' attitudes towards material reuse within the Belgian construction context, where policy ambitions coexist with market barriers, and how they influence the effectiveness of emerging digital tools such as digital building logbooks, material passports, and reuse marketplaces. An interactive workshop with Belgium-based building designers used generative collages to access unconscious associations and bypass social desirability biases. The analysis of collages and descriptive narratives considered affective, behavioral, cognitive and values components. Findings show that designers' attitudes toward reuse are primarily rooted in biospheric and altruistic values, with hedonic values playing a consistent and influential role. Participants expressed optimism, framing reuse as transformation and value creation rather than simple substitution, while also reporting apprehension regarding uncertainty, limited trust in reused materials, and a perceived external locus of control. The study highlights that strengthening re-use through digital tools requires aligning information with designers' value structures, lowering cognitive effort through defaults and streamlined processes, and reinforcing collective and past positive actions through feedback, demonstrating how behaviorally informed tool design can support circular construction in practice.

Keywords: material reuse · designers' attitudes · decision-making digital building logbooks · circular construction

1 Introduction

The construction sector is highly material-intensive and generates substantial waste, making circular strategies such as reuse, adaptability, and extended service life central to reducing primary material extraction and construction waste. European policies

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increasingly emphasize digitalization as a lever for advancing circularity in the built environment [1, 2]. Digital Building Logbooks (DBLs), material passports, and linked reuse marketplaces are expected to improve traceability, information exchange, and lifecycle management, thereby enabling more efficient reuse of materials [3, 4].

However, the availability of digital tools alone does not guarantee adoption. Studies in the Architecture, Engineering, and Construction sector indicate that technological maturity is not the main barrier; rather, behavioral, organizational, and market-related factors constrain implementation [5, 6]. In Belgium, institutional and market challenges are identified as more significant obstacles to circular transition than technical indicators [7], and previous research shows that architects rely primarily on experience and client demands rather than decision-support tools in their design processes [8, 9]. Tools are adopted when they improve design quality and reduce complexity by solving problems existing practices cannot address, rather than by providing added information.

These findings from previous studies suggest that advancing circular design and construction requires understanding how designers perceive reuse, how they evaluate its risks and opportunities, and how digital infrastructures can align with professional values and decision-making practices. Building on this insight, the current research investigates how tacit knowledge shapes building designers' attitudes towards material reuse in the Belgian context, and how these attitudes influence the potential adoption of digital tools intended to support circular construction.

2 Theoretical Framework and Methodology

Understanding why technically feasible reuse strategies are not systematically adopted requires attention to the behavioral determinants shaping professional decision-making. The Theory of Planned Behavior (TPB) posits that behavior is guided by intentions, which depend on attitudes, perceived social expectations, and perceived behavioral control, that is, whether individuals feel they have the capability, resources, and opportunity to act [10]. When perceived behavioral control is low, positive intentions may not translate into implementation. This is particularly relevant in professional contexts, where time constraints, risk, and responsibility influence decisions. Internally motivated intentions are also more likely to be enacted than those driven primarily by external pressures [11]. The TPB has been applied to designers' decisions in sustainable material specification, waste minimization, and heritage conservation, highlighting the importance of attitudes and perceived control in professional practice [12–15].

To analyze attitudes more closely, this study adopts the ABC model, which distinguishes affective (emotions), behavioral (intentions and action tendencies), and cognitive (beliefs, perceived barriers, and enabling conditions) components [16]. Emotions influence how situations are evaluated and whether action feels attractive or risky and have been shown to shape environmental decision-making and technology acceptance [17, 18]. Attitudes are grounded in relatively stable value orientations that guide what individuals consider important [19]. In environmental contexts, biospheric values (concern for nature and ecosystems) and altruistic values (concern for others and society) are often associated with pro-environmental behavior, whereas hedonic values (seeking pleasure, comfort, and aesthetic satisfaction) and egoistic values (seeking status,

power, or personal gain) may inhibit action when the behavior is perceived as costly in terms of effort, time, or comfort [20, 21]. This connects to the "hassle factor", whereby anticipated complexity and cognitive burden discourage sustainable behavior despite favorable attitudes [22]. Together, these concepts provide the analytical lens to examine how designers interpret reuse, how they emotionally and cognitively evaluate it, and why positive orientations may or may not translate into practice.

An interactive focus group with 11 architecture professionals was conducted in Brussels in October 2023. Participants engaged in a generative collage exercise exploring tacit meanings associated with material reuse, followed by recorded group discussions. The dataset consisted of visual materials and transcribed narratives, analyzed using the ABC framework and four value orientations [20] through qualitative content and thematic coding.

3 Results

Participants described reuse of materials using both positive and ambivalent terms, from opportunity and value to uncertainty and disruption. Across collages and narratives, recurring patterns converged around three central beliefs: reuse is (or should be) beautiful; it requires collaboration; and it is urgent.

At the level of values, biospheric orientations are most frequently expressed, followed by hedonic and altruistic values. References to nature, including landscapes, trees, ecosystems, and sustainability, appear consistently across images and narratives. However, climate change is rarely mentioned explicitly, suggesting that environmental concern is not primarily framed in carbon or emission terms. As one participant noted, climate action "it is more of a way of life, reducing global warming is not just about materials". Altruistic values are expressed through emphasis on collaboration and inclusivity, for instance in statements such as "everyone needs to be included" and in images depicting collective action. Hedonic values play a central role in how reuse is perceived. Beauty, charm, and poetry are repeatedly associated with reused materials, often framed as opportunities for reinterpretation rather than compromise. The image of a kintsugi-repaired plate, described as "seeing the beauty of the imperfect", illustrates how repair and reuse are linked to aesthetic appreciation and value creation (Fig. 1). Egoistic values appear less frequently and are primarily described as external barriers, for example through criticism of consumption-driven preferences for novelty and short lifecycles.

Emotionally, reuse is largely framed in positive terms. Following Plutchik's classification [17], joy is the most frequently identified emotion, followed by anticipation. Participants describe hope, curiosity, and willingness to experiment, often combined with urgency, as reflected in the statement "we need to do it now and don't push it any further". At the same time, apprehension emerges in relation to uncertainty and lack of trust, particularly regarding material quality and unclear processes. In one instance, frustration with the pace of change was expressed physically when a participant tore apart the collage support, stating "we need a second world before 2030 because that's already in seven years and we are not doing enough yet". This episode reflects a tension between aspirational commitment to reuse and perceived systemic inertia.



Fig. 1. Collage illustrating the aesthetic reframing of repair and reuse exemplifying the role of hedonic values in shaping attitudes toward reused materials.

From a behavioral perspective, reuse is understood as an active and deliberate design choice rather than a simple substitution of materials. Participants describe it through verbs associated with creativity and experimentation, such as create, reinterpret, and transform. Demolition is framed as the opposite of this approach and, as one participant stated, "demolition is design failure". Reuse is associated with intentional decision-making and responsibility, requiring designers to "try and see what can work". Perceived material value influences these choices, as illustrated by references to marble as desirable for reuse and glass as more readily discarded. Beyond material selection, participants address reuse across multiple scales of the built environment, including landscape, buildings, structures, and space. Reuse is linked to limiting expansion into the landscape and to reinterpreting existing spaces, suggesting that it is conceived not only as material recovery but as spatial and structural continuity over time.

At the cognitive level, participants articulate both barriers and enabling conditions. Barriers include lack of knowledge, uncertainty, complexity, financial and time constraints, prevailing market mindsets, and inaction. Designers question "how are we dealing with these uncertainties?" and observe that "new sells better", indicating the influence of market logics. Reuse is sometimes perceived as slower and more demanding, requiring shifts in expectations regarding value and durability. At the same time, enabling conditions are strongly emphasized. Participants refer to valuing materials differently, improving affordability, strengthening collaboration, and accelerating policy support. Data, transparency, marketplaces, and technology are repeatedly mentioned as critical infrastructures to reduce uncertainty and increase trust, for example through labelling, measuring, and tracking materials. Technology is not described as lacking, but as insufficiently integrated into existing workflows.

Overall, designers appear solution-oriented: 79% of coded references relate to enablers, while 21% refer to barriers (Fig. 2). Data is the most frequently cited enabler,

followed by policy intervention. However, despite identifying multiple solutions, participants display a pronounced external locus of control [23]. Only 19% of references to enabling actions are attributed to architects' own decisions, with most responsibility assigned to policy frameworks, market structures, and broader institutional and supply-chain constraints (Fig. 3). This gap between positive orientation and perceived behavioral control frames the conditions under which reuse can be scaled in practice.

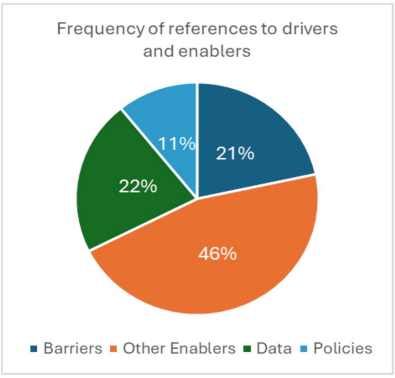


Fig. 2. Frequency of references to barriers and enablers.

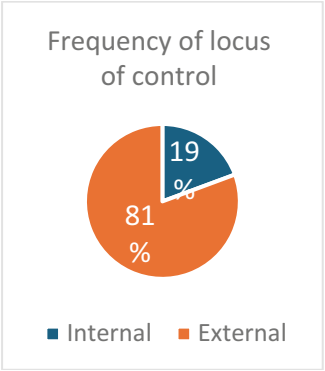


Fig. 3. Frequency of locus of control of enablers.

4 Discussion and Implications

The results show that designers generally view reuse positively, associating it with environmental concern, collaboration, and creative opportunity. At the same time, this optimism coexists with uncertainty and limited trust in reused materials. Together, these findings reveal a gap between positive attitudes towards reuse and the perceived ability to implement it in practice, highlighting the importance of considering behavioral determinants when designing digital tools to support reuse.

Behavioral change interventions do not directly alter behavior but instead act on its underlying determinants [24]. Values, which are relatively stable over time, therefore represent a crucial entry point for transformation. While pro-environmental action is commonly associated with biospheric and altruistic orientations [20], the present findings show that these values coexist with hedonic motivations. Designers repeatedly frame reuse not only as environmentally responsible but as aesthetically rewarding and creatively stimulating. As Steg [20] notes, even individuals with strong hedonic values engage in pro-environmental behavior when it becomes the most pleasurable option. Reinforcing positive actions already in place, such as the adaptive reuse of existing buildings (historic feedback), or providing information about the story, history, and heritage value of reused materials (information provision), may therefore contribute to emission reductions by activating value orientations other than carbon awareness. Increasing circularity is not primarily about strengthening environmental messaging, but about aligning reuse practices with designers' existing professional and aesthetic values.

The results also highlight a gap between motivation and perceived behavioral control. In line with Bouman et al. [21], participants identify strongly with biospheric and altruistic values, yet frequently attribute egoistic motivations to others, particularly market actors. Enabling conditions such as regulation, data availability, and market demand are perceived as decisive, but largely external to the designer's own influence. Whether designers in practice have greater actual behavioral control and can act as change agents in the construction sector than they themselves perceive remains an open question. Nevertheless, this limited perceived behavioral control may reduce the likelihood that positive intentions translate into action. Interventions that make collective progress visible may help address this gap. In the context of digital reuse platforms, this could include accounting for CO_2 saved together through platform use (group-based feedback) or benchmarking a designer's reuse material score against peers in the same geographical area (social comparison feedback).

Emotional dynamics further clarify these mechanisms. Participants oscillate between optimism and apprehension, reflecting commitment to reuse alongside concerns about uncertainty and reliability. Emotions shape decision-making by amplifying perceived risks or rewards [18]. Trust-building measures, transparency, and credible performance data are therefore central to strengthening perceived behavioral control. At the same time, anticipated hassle and cognitive burden may inhibit action, consistent with the "hassle factor" described by de Vries et al. [22]. Designers expressed concern that reuse introduces additional complexity into already constrained workflows. Reducing cognitive effort, simplifying procedures, and embedding reuse as a default option within digital tools may thus be more effective than providing additional technical solutions alone.

5 Conclusion

In conclusion, the findings indicate that advancing reuse in the built environment requires more than technical optimization or one-to-one material substitution. Designers already hold value orientations compatible with circularity and often approach reuse as a creative opportunity. The main challenge lies in strengthening perceived behavioral control and reducing cognitive friction while reinforcing collective momentum. Digital tools such as DBLs and marketplaces can support this transition when designed as behaviorally informed instruments aligned with professional values and decision-making practices.

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A Living Lab Approach to Circular Economy in the Built Environment: Co-designing a Theory of Change for Bio-based Underfloor Heating Systems

Carmen Abril[1(✉)], Fernanda Barzallo[1], Angeles Blanco[1], Per Engstrand[2], Carlos Negro[1], and Sonia Quiroga[1]

[1] Facultas Ciencias Económicas y Empresariales, Universidad Complutense de Madrid, Madrid, Spain
cabrilba@ucm.es

[2] FSCN Research Centre, Department of Engineering, Mathematics and Science Education, Mid Sweden University, Sundsvall, Sweden

Abstract. This paper presents a multi-stakeholder Living Lab addressing construction waste reduction through the redesign and adoption of recyclable, bio-based underfloor heating systems. Through stakeholder mapping workshops and semi-structured interviews with municipalities, material producers, construction companies, waste managers, and policy actors, we identify systemic barriers to circular material adoption: procurement frameworks prioritising lowest cost over lifecycle impact, resistance to innovation among practitioners, lack of material standardisation for reuse, and absence of mandatory material registries. After alignment workshops, the redesigned bio-based underfloor prototype was produced and installed in a university room and a kindergarten for validation, where material performance and user satisfaction are measured, providing empirical evidence for bio-based technology viability in real-world conditions. Our contribution lies in documenting the co-design process that shapes circular innovation pathways in the built environment, suggesting scalable strategies for bio-based material integration and addressing the gap between circular economy ambitions and construction sector realities.

Keywords: Construction Waste · Circular Economy · Bio-based Materials · Multi-stakeholder Collaboration · Living Labs

1 Introduction

The construction and demolition sector is one of the largest contributors to waste generation in Europe, accounting for approximately 37% of total waste produced across EU member states [1]. Within this context, heating infrastructure represents a particular challenge in terms of both energy cost and problematic waste streams: conventional systems require high-temperature water (>60 °C) and rely on mineral-based materials that

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are difficult to separate, recycle, or reintroduce into productive cycles at end-of-life. As the European Union accelerates its circular economy transition through the European Green Deal and associated regulatory frameworks, the built environment has come under renewed scrutiny as both a source of systemic inefficiency and a domain of significant transformation potential [2].

Circular economy (CE) principles offer a compelling reorientation of how buildings are designed, constructed, and ultimately deconstructed. Rather than following a linear take-make-dispose model, circularity demands that materials retain value across multiple lifecycles, that waste is designed out, and that buildings function as material banks rather than material sinks [3]. Bio-based materials—derived from renewable biological sources—are particularly promising candidates, combining lower embodied carbon, biodegradability or recyclability, and the potential for closed-loop material management. However, even after technical solutions have been developed, widespread industry adoption remains constrained by a complex web of regulatory, economic, behavioural, and knowledge-related barriers.

This paper presents a work-in-progress project employing a Living Lab methodology to investigate the development, implementation, and adoption of bio-based, recyclable underfloor heating systems as a circular alternative in existing buildings. Two real-world installation sites in Sweden—a university building and a nursery school—serve as experimental environments in which technical performance, user acceptance, and stakeholder dynamics are simultaneously evaluated. The project is explicitly co-designed: citizens, construction companies, municipalities, and policy actors collaborate closely with researchers, material producers and waste managers to redesign the products, adapt the processes, and develop the new prototypes—co-developing the conditions under which circular transitions become feasible.

2 Circular Economy in the Built Environment

Although societies have always recycled materials (stone, wood, bricks, metals, paper) out of scarcity and economic necessity, the CE concept gained global prominence in the 2010s as a model designed to minimize waste by keeping products, materials, and systems in use for as long as possible, moving from niche academic discourse to mainstream policy driven by recognition that resource consumption is structurally unsustainable at current demands.

The construction sector is resource-intensive and lifecycle thinking has become a priority. CE principles have been applied through concepts such as design for disassembly, material passports, urban mining, and reversible buildings [3, 4]. The Ellen MacArthur Foundation's framework of inner loops—reuse and repair over recycling and recovery—has been particularly influential in the built environment [5]. In 2015, the sector was included in the first EU Circular Economy Action Plan, and buildings have since been considered "materials banks". Despite this conceptual richness, empirical evidence on CE adoption in construction practice remains sparse. The sector is characterized by long asset lifetimes, fragmented value chains, project-based procurement, and a risk-averse innovation culture [6]—structural features creating path dependencies that reproduce conventional material choices even when circular alternatives are technically and economically viable. A recurring finding is that barriers to circularity are not

primarily technical but institutional and behavioural: procurement frameworks, upfront cost, lack of trusted data on material quality and provenance, and absence of incentive alignment across actors [7].

Bio-based materials occupy an important but contested position within circular construction. They offer genuine environmental advantages—lower embodied carbon, renewable feedstocks, and closed-loop recyclability at end of life—yet face significant market acceptance challenges related to perceived durability, fire and moisture performance, unfamiliarity among specifiers and contractors, and a regulatory framework calibrated to mineral-based products [8]. Bio-based underfloor heating systems illustrate these tensions: while technical performance can be demonstrated, adoption requires overcoming institutional inertia across the value chain.

3 Multidisciplinary Collaboration as a Precondition for Systemic Change

The systemic nature of CE transitions implies that no single actor or discipline possesses the knowledge or leverage to drive change unilaterally. Municipalities set procurement standards and zoning; material producers determine what enters the market; construction companies mediate between design intent and physical reality; waste managers define what happens at end of life; and end users shape demand [10]. This interdependence reflects a socio-technical system in which technological change is inseparable from institutional arrangements, market structures, cultural practices, and governance dynamics: transformations emerge not from isolated innovations, but from coordinated changes across multiple system dimensions simultaneously [9].

Multidisciplinary collaboration in this context means more than assembling diverse stakeholders: it requires structured knowledge translation across disciplinary and sectoral boundaries, mechanisms for negotiating conflicting interests, and shared frameworks for evaluating success. Recent CE research indicates that collaboration failures often stem not from technological limitations, but from fragmented information flows, asymmetries in decision-making power, and the absence of common performance metrics across the building lifecycle [20]. In this project, stakeholder mapping workshops were used as an initial instrument to identify the full ecology of actors implicated in the adoption of bio-based heating systems, and to map the collaborative and antagonistic relationships between them. Such participatory approaches are increasingly indicated in transition management and Living Labs as essential for identifying leverage points, institutional lock-ins, and opportunities for coordinated intervention, with well-demonstrated potential to drive sustainable development, particularly in the bioeconomy sector [20].

Semi-structured interviews with municipalities, construction firms, material producers, waste managers, and policy actors revealed a consistent pattern of systemic misalignment: each actor acknowledged the desirability of circular transitions, yet located barriers primarily in the behaviour of other actors—absent standardized material data, client risk aversion, lowest-cost procurement frameworks, and missing material registries. This mutual attribution is diagnostic of a collective action problem that cannot be resolved unilaterally.

A further challenge concerns the temporal mismatch between economic incentives and environmental benefits: many construction actors operate within short investment cycles that prioritize immediate cost minimization over lifecycle performance, systematically disadvantaging reusable, adaptable, and bio-based materials despite their long-term value [11]. CE transitions therefore require institutional mechanisms aligning financial incentives with long-term sustainability objectives.

The research project described here explicitly addresses this collective action dimension: bringing multiple stakeholder categories into a shared Living Lab environment creates conditions for mutual learning, joint problem-framing, and collaborative solution development, and generates evidence—on material performance, user acceptance, and process effectiveness—that can build the trust needed to shift procurement practices and professional norms.

3.1 The Living Lab Framework and Its Application in This Project

Living Labs are open innovation environments in which products and systems are developed, tested, and refined in real-world settings with the active participation of end users and other stakeholders [11]: unlike controlled laboratory experiments, they operate in the complexity of actual social and physical environments, and unlike purely consultative processes, they generate empirical data alongside stakeholder engagement. In circular construction, Living Labs have been used to test material innovations, evaluate retrofit strategies, and explore new business models for resource recovery [12]. Because multiple stakeholders participate in defining questions and interpreting results, they accelerate the social learning that underpins systemic change.

This project operates in one Living Lab where prototypes were co-designed, tested and validated at two Swedish locations: a renovated meeting room in a university building and a nursery school classroom. These sites were deliberately selected for their distinct user profiles (academic staff and students; teachers and young children), organizational contexts, and patterns of floor use that may differentially stress the material's thermal and mechanical performance. At the university, conventional radiators were replaced by recyclable underfloor heating; at the planned nursery, recyclable floors were considered as part of the municipality's requirements.

The Living Lab process encompasses three phases: first, stakeholder mapping and semi-structured interviews characterized the barrier landscape; second, the installations are presented for stakeholder approval; third, the bio-based underfloor heating system is installed and its technical performance, energy savings and end-user satisfaction are quantified. Material performance is compared with traditional heating floors based on expanded polystyrene foam, and energy savings with respect to traditional radiator systems. Finally, user perceptions are captured through structured surveys covering functional, emotional, and experiential dimensions, drawing on prior research on indoor environmental quality, material experience, and public acceptance of sustainable technologies [13, 14]. Functional perception captures attributes such as thermal comfort, noise, slipperiness, and cleanability; emotional perception covers affective responses such as comfort and pleasantness; experiential perception evaluates tactile qualities (temperature, smoothness, resistance) through direct interaction with the floor surface;

an additional module assesses attitudes toward circular materials relative to conventional alternatives.

4 Results

Stakeholder engagement in the first project phase identified three categories of systemic barrier to bio-based circular material adoption.

First, procurement frameworks in both the public and private sectors remain strongly oriented toward upfront cost minimization, with limited capacity to incorporate lifecycle cost or environmental impact assessments—a structural disadvantage for bio-based alternatives whose lifecycle advantages are not captured in conventional metrics. Moreover, through substitution of fossil-based alternatives, forest-sector products reduce fossil CO_2 emissions by over 200 million tons annually in the Nordic-Baltic region alone [15].

Second, resistance to innovation among construction practitioners was identified as a significant barrier, rooted in risk aversion, unfamiliarity with the new bio-based 3D-paper composite materials, and negative beliefs about their moisture performance.

Third, EU countries differ in how they follow the "waste ladder" of EU Directive 2008/98/EC on waste [21], whose intentions this project follows: in Sweden, zero organic waste goes to landfill, compared with more than 100 Mt./y in the rest of the EU. Bio-based heated underfloors consist of 82% paper (FSC-certified mechanical, semichemical, chemical and/or recycled pulp-based liner, fluting and inner liner) and 18% aluminium, with water pipes inserted within this matrix. When dismantled, the materials are easily separated for traditional recycling cycles. Strength results of hot-pressed papers show that conventional fossil-based EPS foam could be replaced without problems, except that the bio-based paper composite is more expensive.

For use in wet areas, however, the wet strength and moisture resistance of the "heat-board" must be further improved, which can be achieved with a new hot-pressing technology for the paper materials in the 3D-composite board. With hot-pressed paper from chemithermomechanical pulp (28% lignin content if made from spruce), dry tensile strength increases by 50–150%, depending on whether the starting material is a semi-chemical pulp such as NSSC (high starting value) or a low-energy chemithermomechanical pulp such as HTCTMP (low starting value). Laboratory sheets and industrially produced paper were hot-pressed in lab- and pilot-scale machines; example dry-strength results (tensile index) are shown in Fig. 1, partly based on research published by Joelsson et al. [16–18].

In addition, this combination of elevated temperature and pressing conditions significantly improves wet strength, retaining 20–35% of the dry tensile index, depending on the hot-press conditions, while untreated materials exhibit no measurable wet strength, examples are shown in Fig. 1.

More fundamental studies indicate that hot-pressing of paper materials consisting of lignin-rich fibers recreates fiber–fiber bonds close to those in native wood, which means that paper with both high dry and high wet strength is achieved. Experimental results show a pronounced increase in wet strength above 175 °C, which correlates with lignin softening and enhanced fiber–fiber bonding in the simulation studies [19]. These findings highlight the ability of molecular simulations to elucidate the mechanisms of

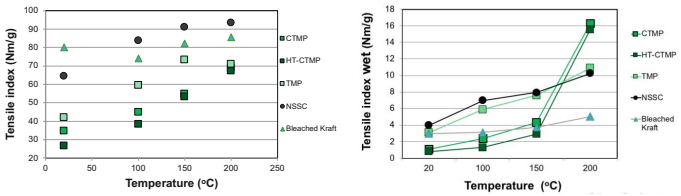


Fig. 1. Dry (left) and wet (right) tensile index as a function of hot-pressing temperature of paper made from high yield pulps (TMP, CTMP and HTCTMP), semichemical pulp (NSSC) and bleached kraft pulp.

lignin-driven bonding and provide a foundation for optimizing the use of lignin-rich materials in various applications; see Fig. 2.

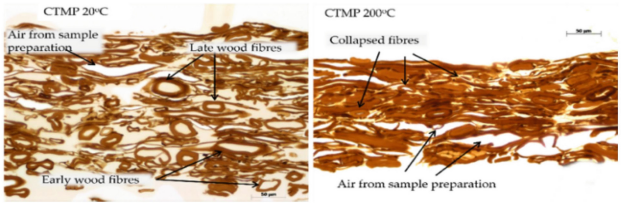


Fig. 2. SEM images of paper sheet cross sections: (a) reference sample, (b) 180 °C moist, (c) 260 °C dry, and (d) 260 °C moist. Red and blue markings show areas where the interface (at 260 °C) between neighboring fibers becomes invisible under moist but not dry conditions.

The implementation of the bio-based 3D-paper composite heating floor yielded several empirical results: installation was completed in two working days without major disruption to the building; the new system adapted perfectly to the existing water heating circuit, confirming compatibility with traditional systems; and the room was furnished (carpet, two large meeting tables, twenty chairs with wheels) without any technical problem, confirming in use the resilience demonstrated in the laboratory.

Regarding user perception, preliminary data suggest broadly positive acceptance of the bio-based floor, with functional ratings comparable to conventional alternatives and emotional perception scores above neutral, consistent with prior research on user acceptance of sustainable building materials [15].

5 Toward a Theory of Change for Circular Construction

The Living Lab methodology and multi-stakeholder engagement process described here are oriented toward developing not only practical implementation strategies but also a theory of change: an account of the causal mechanisms through which circular transition in construction can be achieved, and of the interventions most likely to activate them.

Based on the empirical findings, a nascent theory of change can be articulated around three interlocking mechanisms. The first is evidence-based legitimation: the generation

of credible performance data, both technical and experiential, that enables decision-makers to justify circular procurement choices against the dominant cost-minimisation logic; the Living Lab is the primary instrument for generating this evidence in real-world conditions. The second is stakeholder alignment: the structured engagement of actors across the value chain to surface misalignments, build mutual understanding, and develop shared frameworks for assessing value, initiated through the mapping workshops and interviews and to be consolidated in the third-phase co-design workshops. The third is institutional embedding: the translation of project learnings into procurement frameworks, professional standards, and regulatory instruments that normalise circular material choices.

Together, these mechanisms constitute a theory of change that is neither purely top-down (regulatory mandates) nor purely bottom-up (individual innovation), but systemic: it operates simultaneously at the levels of evidence, relationships, and institutions, coordinating action across multiple leverage points [9].

6 Conclusions

This paper has presented a Living Lab project investigating the redesign and adoption of bio-based, recyclable underfloor heating systems as a contribution to circular economy transitions in the built environment. Its principal methodological contribution is the integration, within a single Living Lab framework, of multi-stakeholder co-design, technical performance measurement, and user perception research—reflecting the core argument that circular transitions in construction are inherently socio-technical.

The findings confirm the systemic character of the barrier landscape: procurement frameworks oriented toward upfront cost minimization, practitioner resistance rooted in risk aversion and unfamiliarity with bio-based materials, and considerable differences in the implementation of EU waste-hierarchy regulations across member states. The Living Lab implementation confirms the feasibility of the innovative material, its energy-saving efficiency, user acceptance, and end-of-life recyclability advantages.

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Design for Deconstruction: Closing the Material Loop in Malta's Construction Industry

Sarah Muscat[1], Rebecca Emily Dalli Gonzi[1(✉)], and Simon Paul Borg[2]

[1] Department of Construction and Property Management, Faculty for the Built Environment, University of Malta, Msida, Malta
rebecca.e.dalli-gonzi@um.edu.mt

[2] Department of Environmental Design, Faculty for the Built Environment, University of Malta, Msida, Malta

Abstract. The construction industry is frequently criticized for its contribution to global resource depletion, particularly through the disposal of materials from end-of-life buildings. Closing the material loop by transforming waste into a resource is essential for achieving a more sustainable and circular built environment. Design for Deconstruction (DfD), also referred to as Design for Disassembly, is a waste minimization strategy that enables buildings to be dismantled at the end of their service life, allowing components and materials to be reused or recycled rather than landfilled. This study investigates the potential for implementing DfD within the Maltese construction industry, where construction and demolition waste remains a significant environmental concern. A quantitative research approach was adopted through the distribution of a survey among key industry stakeholders to assess current practices, levels of awareness, perceived barriers, and potential drivers for adoption. The findings indicate that time and cost constraints, limited education and training, entrenched industry culture, and existing policies and regulations represent major obstacles to DfD implementation. However, financial incentives, strengthened regulatory frameworks, and enhanced professional training emerged as key enablers that could facilitate wider adoption. Although carried out within the Maltese context, the results reflect broader challenges faced by small islands and resource-constrained regions, highlighting DfD's wider applicability as a systemic strategy for promoting circular construction and reducing waste in the built environment.

Keywords: End-of-life · Design for Deconstruction · Material Reuse · Barriers · Strategies

1 Introduction

The construction industry is among the most resource-intensive sectors globally, significantly contributing to material consumption, energy use and waste generation [1]. A substantial portion of this impact occurs at the end-of-life stage of buildings, where demolition remains the dominant practice, leading to the loss of valuable materials that could otherwise be recovered and reused [2]. This linear '*take-make-dispose*' model

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intensifies energy consumption, greenhouse gas emissions, natural resource depletion and landfill pressure. In response, circular economy principles promoting reuse, recycling and regeneration have gained prominence [3, 4]. Design for Deconstruction (DfD) represents a key waste minimization strategy, enabling buildings to be dismantled rather than demolished. By integrating de-constructability into the design phase, DfD facilitates material recovery and reuse, reduces waste generation, enhances resource efficiency and supports long-term environmental sustainability [5, 6].

The Maltese Islands present a critical context due to high population density, limited land availability and intense construction activity. Construction and Demolition Waste (CDW) constitutes a significant share of the national waste stream, with landfilling and quarry backfilling remaining the predominant disposal methods [7]. Such practices are unsustainable in the long term and misaligned with the EU's circular economy goals [8]. This paper explores the potential of implementing DfD in Malta to reduce construction waste and simultaneously promote material reuse through sustainable design. It assesses stakeholder awareness, current practices, and barriers to adoption, while identifying strategies to support integration. Although centered on Malta, the findings are relevant to other regions facing similar environmental challenges.

2 Literature Review

2.1 Construction Waste and Circular Economy

The construction industry plays a vital role in national economies, as it shapes the built environment and by being an important economic driver [8]. However, this sector is among one of the most resource-intensive sectors [9], driven by urban redevelopment, building obsolescence, and short design lifespans [10, 11]. Unsustainable construction practices often prioritize disposal rather than value retention, leading to the loss of embodied energy and materials, intensifying resource scarcity, and contributing to climate change [2]. Circular economy challenges this, as it turns waste into a resource by closing the material loop [3, 4].

Circular strategies in the built environment include material reuse, recycling, adaptive reuse and life-cycle-based design. DfD aligns well with these circular principles by enabling high-quality material recovery for reuse, which generally provides greater environmental benefits than recycling [5, 12, 13].

2.2 Design for Deconstruction (DfD)

DfD is an approach in which buildings are intentionally designed for disassembly at the end of their service life, enabling the reuse and recycling of recovered materials [13]. It requires strategic consideration of material selection, structural systems, accessibility and documentation. By promoting resource efficiency DfD delivers environmental and economic benefits, including embodied carbon preservation, waste reduction, job creation and the growth of secondary material markets [2, 14–16].

Theoretical models such as Brand's shearing layers conceptualize buildings as dynamic systems composed of components with varying lifespans [17]. Designing these layers for easy separation facilitates effective deconstruction [18].

2.3 Barriers to DfD Adoption

Despite its recognized benefits, DfD remains underutilized in the construction industry with several recurring aspects being identified in literature as potential barriers, including higher perceived upfront costs, lack of regulatory incentives, fragmented industry structure, limited market demand for reused materials, limited education and training among built environment professionals and cultural perceptions regarding the quality and reliability of reused materials [13–16]. These barriers are especially evident in contexts where demolition has been normalized and where policy frameworks do not promote circular strategies [2].

2.4 The Maltese Context

Over the years, CDW management in Malta has relied heavily on landfilling and quarry backfilling. Recycling practices such as the reuse of stone and the crushing of concrete for aggregate, are currently in place; however, more sustainable long-term strategies need to be implemented [8, 19]. The Maltese context is characterized by a strong demolition culture, constrained land availability, and a regulatory framework which has not incentivized circular construction strategies. These conditions make Malta a particularly relevant case for investigating the feasibility and challenges of implementing DfD.

3 Methodology

3.1 Research Design

The study adopts a quantitative research approach by developing a structured 18 question survey, consisting of 11 closed 'Yes' or 'No' questions and 7 Likert scale structured questions, allowing for both quantifiable responses and additional open-ended comments. This was done to best capture stakeholder perspective on end-of-life practices, awareness of DfD, perceived barriers, and potential drivers [20].

The survey targeted key stakeholders within the Maltese construction industry including warranted architects and engineers, contractors, developers and clients. To encourage truthful reporting, data was collected anonymously. Although the Maltese market size is small a total of 125 respondents participated in this study, 38 of which were clients, 13 were contractors and 74 were warranted architects and engineers, referred to locally as 'Perit'. Even though the sample size was considered acceptable to produce statistically meaningful and reliable results, the contractor participation remained relatively low compared to other stakeholder groups. This potentially may have affected the representativeness of contractor perspectives.

3.2 Data Analysis

Quantitative data was analyzed through the use of the Chi-Square and the Kruskal-Wallis tests, where the relationship between the respondent characteristics, such as professional role, age, and their attitude towards deconstruction, material reuse and end-of-life, was examined [20].

4 Results

4.1 Current Practices and Respondents Awareness

Although this is not yet reflected in current industry practice, overall results show that a vast majority of the respondents recognize deconstruction as a preferable end-of-life strategy, as shown in Fig. 1. A clear gap therefore exists between theoretical acceptance and practical implementation within the Maltese construction industry.

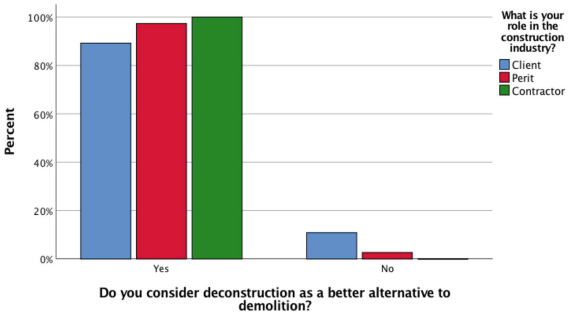


Fig. 1. Respondents choice between choosing deconstruction as an alternative to demolition, sub-divided by role.

When asked if they use recycled or reused material/products in their projects (Fig. 2) or if they think on what will happen to the materials after a building end-of-life (Fig. 3), the results however show a different picture altogether, as only a minority of respondents reported considering end-of-life outcomes to buildings, especially during the design stage. Some participants argued that buildings are intended to last for a considerable number of years, rendering such considerations unnecessary. As a result, design decisions continue to be dominated by cost, aesthetics, and regulatory compliance, reinforcing a linear '*take-make-dispose*' building model, further highlighting the gap between sustainability and everyday design practice.

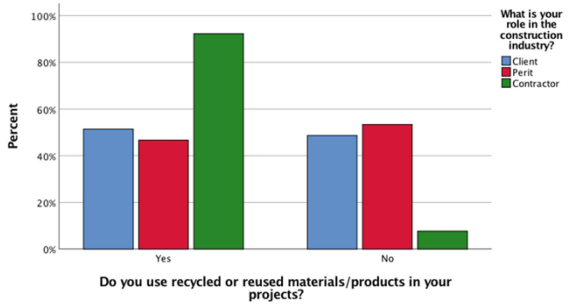


Fig. 2. Respondents use of recycled or reused material/products in their projects, sub-divided by role.

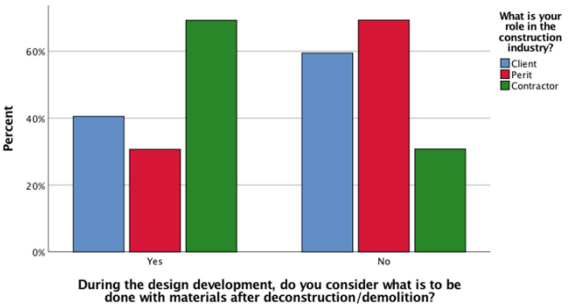


Fig. 3. Respondents consideration of what will happen to the materials after a building end-of-life, sub-divided by role.

Although some respondents reported the use of recycled or reused materials, such practices are mainly used in conservation projects, where materials such as traditional stone components are reintegrated into the development. Other recycled materials are typically down cycled and utilized for backfilling operations. This suggests that these practices are not primarily driven by sustainability objectives.

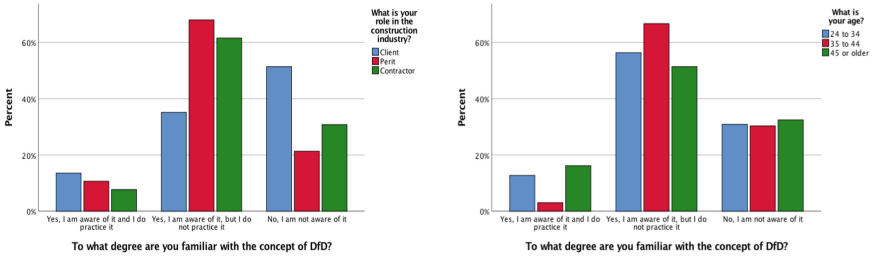


Fig. 4. Degree of familiarity of the concept of DfD sub-divided by (*left*) the role of the respondents, and (*right*) by age of the respondent.

Awareness of DfD varied significantly among stakeholder groups. Figure 4 *left* shows how professionals demonstrated higher familiarity with this concept compared to developers and contractors. This generational shift was particularly evident in younger professionals, as shown in Fig. 4 *right*.

4.2 Barriers to Implementation

Several key barriers to the adoption of DfD were identified and rated across the three main stakeholders' groups as shown in Fig. 5. While these barriers are consistent with previous international research, the findings demonstrate how they collectively reinforce demolition-oriented practices within the Maltese construction industry.

– **Time and cost constraints:** Respondents earmarked this as a major concern, with DfD perceived as more expensive and time-consuming than conventional demolition.

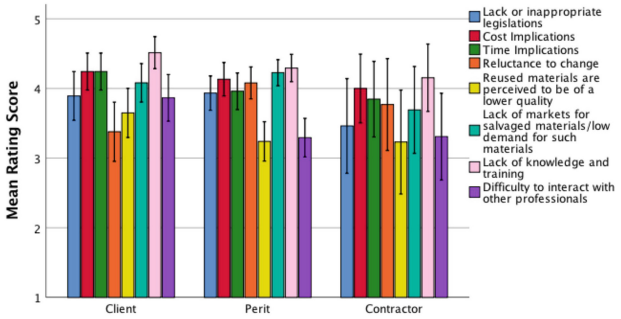


Fig. 5. Respondents rating of potential barriers to DfD.

Open-ended responses, revealed that the long standing perception is that developers prioritized short-term financial returns over long-term environmental benefits, reflecting the importance of immediate financial returns over long-term environmental value identified in existing literature [14].

- **Limited education and training:** Respondents are conscious of the insufficient knowledge and practical experience related to deconstruction principles. The absence of skilled expertise increases uncertainty and risk aversion within the sector, consistent with prior research on successful DfD adoption [21].
- **Policy and regulation:** Existing regulatory frameworks neither incentivize deconstruction nor discourage waste-intensive demolition practices. Aligning with existing literature indicating that DfD adoption is more likely when supported by policy incentives [14], respondents argued that without appropriate legislation, the implementation of DfD would remain unrealistic.
- **Industry culture:** A strong demolition culture is present, reinforced by risk aversion and skepticism towards reused materials. Respondents reported negative client perceptions of reused materials and reluctance to change. Previous research indicate that reused materials are often perceived as inferior in terms of safety and aesthetics to first time use materials [21]. Such perceptions reveal that barriers to DfD are not only technical or economic, but also cultural and behavioral.

4.3 Drivers and Enablers

To overcome barriers in adopting DfD principles, several measures were proposed as shown in Fig. 6. These include implementing new policies and stricter regulations (such as tighter landfill rules), offering financial incentives to reduce cost concerns, developing clear technical guidelines, improving education and training, integrating digital tools like BIM, involving demolition and deconstruction professionals early in the design stage, and providing adequate storage facilities for reclaimed materials. Among these, financial incentives were ranked by stakeholders as the most influential in promoting DfD adoption, consistent with previous research [21]. The findings therefore indicate that transitioning toward circular construction will require not only greater awareness, but also broader systemic support.

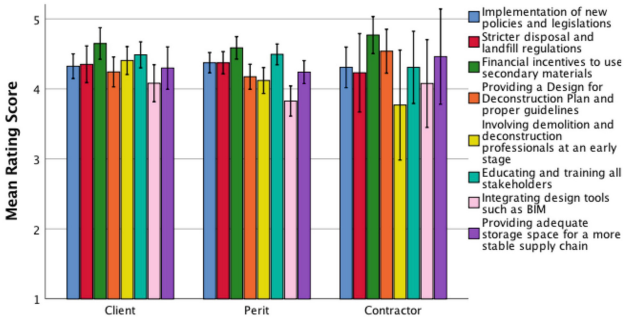


Fig. 6. Respondents rating of potential drivers to DfD.

5 Conclusion

The continued use of linear construction practices is becoming unsustainable, particularly in areas where rapid growth is increasing pressure on land, resources, and waste systems. A shift toward circular lifecycle thinking is needed, with greater emphasis on material recovery and reducing reliance on virgin resources.

The research identifies Design for Deconstruction (DfD) as a practical strategy to reduce construction and demolition waste but highlights a gap between theoretical support for circularity and its real-world application. Major barriers include cost and time pressures, lack of expertise, weak regulatory frameworks, and a demolition-focused industry culture.

Awareness alone is insufficient to drive systematic change. To enable transition, the study recommends financial incentives, stronger policies, technical guidelines, education and training, digital tools, specialist involvement, and improved infrastructure for reclaimed materials. Although focused on Malta, the findings are relevant to other resource-constrained regions. Future research should use life cycle assessment, whole-life costing, and pilot projects to validate the environmental and economic benefits of DfD and support systemic industry reform.

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Market Acceptance of Reused Construction Components in Renovation Projects

Matthias Haase[1](✉), Mihaela Meslec[1], Martina Hefele[1], Gerald Leindecker[2], Maria-Beatrice Andreucci[3], and Marco Delli Paoli[3]

[1] Zurich University of Applied Sciences, Waedenswil, Zurich, Switzerland
matthias.haase@zhaw.ch
[2] FH Upper Austria and IAPL, Wels, Austria
[3] Università degli Studi di ROMA "La Sapienza", Rome, Lazio, Italy

Abstract. Despite the ecological and economic benefits of reusing construction components, widespread market acceptance remains limited. This study investigates the factors driving and hindering the adoption of salvaged materials to develop a strategy for integrating reused components into mainstream renovation and conversion projects. The research involved a systematic analysis of current market acceptance levels and a comprehensive identification of core barriers. By evaluating the role of component and scrap exchanges, the study mapped the landscape of material reuse—from historic quality and aesthetic value to logistical and perception-based hurdles. The primary outcome is towards a Comprehensive Action Plan structured around three interconnected elements. It identifies that while salvaged materials often surpass new products in quality, market growth it currently hindered by logistical uncertainty and perception gaps. The interviews with ten Swiss key stakeholders provide insights into specific interventions for stakeholders and policymakers to bridge these gaps, transitioning component reuse from a niche concept to a mainstream industrial practice. The study concludes that the transition to a circular construction industry requires a collaborative, strategic roadmap to overcome market barriers identified in a first series of interviews. Implementing the proposed Action Plan requires more work to unlock the full ecological potential of building component reuse, and providing a clear path forward for both component exchanges and the broader construction sector.

Keywords: Circular · Reuse · Renovation · Market Acceptance

1 Introduction

As one of the most resource-intensive sectors of the economy, the construction and real estate sector makes a significant contribution to global environmental pollution. In the European Union, it is responsible for around 50% of total raw material extraction and 37.5% of total waste generation [1]. Globally, construction activities account for about 30% of total annual waste, with these figures expected to continue to rise due to population growth and infrastructure needs [2]. In addition, the construction sector is a

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major driver of the climate crisis, as it is responsible for 37% of global greenhouse gas emissions as well as 50% of total material consumption [3]. As a systemic response to this practice, the circular economy is establishing itself as a necessary paradigm shift. Their goal is to minimize resource consumption by keeping materials and products in a closed loop for as long as possible [4].

From an environmental point of view, reuse is clearly superior to recycling, as it avoids the emissions-intensive production phases. Current LCA studies quantify this advantage precisely: Compared to new material inflows, a 75% reduction in greenhouse gas emissions in manufacturing (phases A1–A4) was found. If reused components are compared directly at the component level with new equivalents, the reduction in manufacturing emissions is even up to 90% [5].

Despite these significant environmental benefits, recycling or even landfilling is still the predominant practice in many countries [2]. In reality, prioritizing reuse over recycling often fails due to a crucial hurdle: the lack of reliable data. A comprehensive information deficit is often cited in the literature as the main cause of ineffective recovery and reintroduction of components into the cycle [6]. Senarathne et al. (2025) confirm that the lack of comprehensive material information remains a significant barrier [7]. In contrast to recycling, to reuse a component directly, precise data on condition and properties are necessary, which are often not currently available in existing buildings. This underlines the need for new digital methods to rapidly improve the circularity of the entire sector [3].

Despite the ecological and economic benefits of reusing construction components, widespread market acceptance remains limited. This study investigates the factors driving and hindering the adoption of salvaged materials to develop a strategy for integrating reused components into mainstream renovation and conversion projects.

2 Methodology

The research design of this work is designed as a qualitative, exploratory study (Döring & Bortz, 2016) [8]. This approach was chosen because the design of digital marketplaces in the context of the circular economy is a complex and dynamic field in which subjective perspectives, patterns of action and specific requirements of the actors are in the foreground. Methodologically, the thesis follows a two-stage approach that combines theoretical and empirical findings:

1. In a first step, the theoretical frame of reference was developed through a comprehensive literature and document analysis. This served to record and critically classify the current state of the art, regulatory framework and systematic analysis of current market acceptance levels.
2. Based on this, a qualitative interview study was carried out in the second step. The aim was to mirror the concepts identified in theory with practical experience, to concretize information needs and to identify gaps.

This structure ensures that the design principles developed a comprehensive action plan are not only theoretically sound, but also practically anchored.

2.1 Procedure for Literature Review

The theoretical foundation of the work was based on a systematic literature and documentary analysis. Since the field of investigation of the digital circular economy is characterized by a high level of dynamism and technological innovation, a triangulation of different types of sources was undertaken.

Search strategy and sources: The research was carried out in the period from September to November 2025. To reflect both the state of scientific research and the current market reality, three main categories of sources were used:

Scientific literature: Use of meta-databases (e.g. Google Scholar, ResearchGate) and publishing portals (e.g. ScienceDirect, MDPI) to identify peer-reviewed papers.

Grey literature and standards: Analysis of industry reports, white papers and technical documentation from relevant stakeholders. In addition, specific Swiss standards (SIA 2032, SIA 390/1) and European regulations (ESPR, newCPR) are used as a normative basis.

Practical sources: Direct research on the websites of the analysed platform operators to verify functionalities and business models.

2.2 Sampling (Selection of Examination Units)

The interview partners were selected according to the principle of purpose-led sampling (targeted selection) according to Döring and Bortz (2023) [8]. In this procedure, the study units are not selected at random, but on the basis of defined characteristics that were of central importance for answering the research question.

The aim of the sampling was to depict a maximum variation of perspectives along the entire value chain of construction. Therefore, it was necessary to include experts from all relevant phases.

A total of ten experts were interviewed. The identification and approach of the people was carried out via existing professional networks, targeted research on LinkedIn and Google, and through the supportive identification of relevant professionals. The selection criteria included:

1. Technical expertise: Several years of experience in a specific role in the Swiss construction and real estate sector.
2. Specific reference: Direct points of contact with topics of the circular economy (reuse, recycling), digitization (BIM, data management) or material testing.
3. Role representation: Coverage of the entire process chain (customer, planner, operator, recycler).

The data collection took place in the period from October to November 2025 and was carried out via Microsoft Teams due to the geographical distribution of the participants. All interviews were audio-visually recorded with the consent of the respondents to enable detailed transcription. The atmosphere of the discussions was characterised by openness, with the digital implementation via MS Teams enabling the efficient integration of experts spread throughout Switzerland.

3 Results

The results are based on the qualitative evaluation of a total of 1028 coded text segments. To focus on the central findings, the synthesised core statements are presented in the following sections. Due to its scope, the complete data basis, including all detailed subcodes and assignments, is stored as a separate digital document (Codesys-tem_BA_Graf.xlsx) and serves as an evidence basis for the deductions made here.

The analysis shows that the theoretical role model is often expanded in practice by pragmatic adjustments and new responsibilities.

3.1 Strategic Aspiration and Operational Reality

Especially in the case of public building owners, a gap between aspiration and reality is revealed. While she sees herself strategically as an "enabler" who would have to initiate reuse concepts in early phases such as the preliminary study (Interview E, item 39), operational implementation often depends on the initiative of individual project managers. Binding instructions are often lacking, and processes are not yet established across the board (Interview E, pos. 20, 41–46). In addition, there is an expectation on the part of the building owner that specialist planners and contractors should proactively introduce CE concepts, but this often fails due to their lack of experience (Interview E, items 44–49).

3.2 The New Role of the "Component Hunter"

Between the static existing building and the dynamic new building, a new functional role has emerged with the specialized specialist planner for reuse (often referred to as the "component hunter"). These actors act as translators between the vague data of the existing building and the precise requirements of planning (Interview D, pos. 6–10). Its activities are divided into two directions:

In the case of the source object (dismantling): Here they act as "screeners" who carry out inventories and assess the potential of the existing building.

At the target object (new building): Here, as "hunters", they look for specific components that fit the design (Interview D, pos. 3–4).

3.3 Structural Design Between Safety and Innovation

For engineers, reuse is not an aesthetic end in itself, but a technical challenge. Its role is primarily defined by ensuring its load-bearing capacity and durability (Interview J, item 6). The experts emphasise that reuse (e.g. of steel girders) must not be treated as a "nice-to-have" item but must be ordered by the client as a "mandatory part of the project" (Interview F, item 57). Without this explicit order and the willingness to reward additional expenses, reuse remains a niche in structural engineering (Interview F, item 49).

3.4 Forgotten Facility Managers

A critical process gap is evident in the transition to operation. Facility managers (FM) are often involved too late in defining data requirements. As a result, BIM models or digital twins become "data cemeteries" that contain design data but provide irrelevant or outdated information for operations (Interview A, pos. 4–6). FM often mistakenly sees itself in the role of passive data receiver instead of actively defining requirements for maintenance (e.g. maintenance cycles, warranties) (Interview A, pos. 6, 39; Interview B, item 4).

3.5 Timely Need for Information

Timely availability emerged as critical factor with regard to information requirements. For almost all stakeholders, timing—specifically "time-to-market"—serves as the primary decision criterion. "If the date doesn't work, there's no point in looking any further to see if the quantities match" (Interview D, Pos. 19). Synchronizing the source and target objects constitutes the greatest logistical hurdle, as intermediate storage is to be avoided for cost reasons (in line with "Just-in-Time" principles). Without a guarantee of availability at the required time, effective planning is virtually impossible for engineers and architects (Interview F, Pos. 36; Interview J, pos. 20–22).

3.6 Acquisition for Geometry and State

The requirements for geometric precision are not static, but develop in the course of the project:

(1) Rough survey (screening): Initially, a rough recording (e.g. "40 washbasins", standard dimensions for radiators) is sufficient, as a detailed recording would be too resource intensive if no buyer has been determined (Interview D, pos. 3–8, 10).
(2) Detailed survey: Only if there is a concrete interest in placement is a precise recording made. In this context, purely digital methods reach their limits: The physical condition (e.g. jammed window handles, dismantling) often must be verified by an on-site inspection, as photos alone are not sufficient (Interview D, pos. 27–30, 49–50).

3.7 Pollutants as Knock-Out Criteria

A key obstacle is the data gap on pollutants. Freedom from harmful substances is considered an absolute basic requirement ("As a matter of principle, we do not release anything that we do not know to be free of harmful substances" – Interview D, item 39). Existing dismantling reports are often too inaccurate for a reuse assessment. In addition, experts from industry warn of new risks such as PFAS, which could contaminate entire material flows in the future (Interview C, pos. 35–40; Interview I, pos. 9–16). In the case of supporting structures (steel/concrete), a lack of material documentation (e.g. unknown steel grade or carbonation depth) means that safety factors must be increased, which often nullifies the economic efficiency of reuse (Interview F, items 6–8; Interview J, Pos. 19).

4 Discussion

The roles and demands of the actors were examined. This is where the greatest conflict between the theoretical ideal of the "material bank" and physical reality becomes apparent. The chosen research design of a qualitative, exploratory study with ten expert interviews proved to be expedient in shedding light on the complex, often informal processes of reuse practice. Through the deliberate selection of a heterogeneous sample from component hunters to public builders to industrial recyclers, it was possible to draw a multi-layered picture of the conflicting interests. However, it should be noted that the semi-structured character of the interviews led to thematic digressions in places. Since the interviewees had very different backgrounds, the discussions sometimes digressed into specific specialist areas such as chemical details of pollutants or legal subtleties in liability. This made it difficult to directly compare individual answers in the coding process, but at the same time brought unexpected insights to light, such as the psychological hurdle of cultural scepticism. In addition, the sample shows a certain bias, as most of the experts already had a positive attitude towards circular economy. The perspective of the broad mass of conventionally working architects, who categorically reject reuse due to traditions, was only indirectly recorded.

4.1 Timely Availability

While the theory postulates that buildings act as dynamic material banks and resources circulate through closed loops, practice identifies temporal synchronization as the biggest obstacle [9]. The results show that it is not the material itself that is missing, but the right time window. Without a physical interim storage facility ("buffer"), digital mediation often fails, as a direct "just-in-time" delivery from demolition to new construction is hardly logistically feasible. Experts confirm that components often "silt up" if they cannot be conveyed exactly at the time of dismantling (Interview D, item 67). This puts the theorical assumption into perspective that digital marketplaces alone can solve the problem; rather, it requires concepts that actively address time management.

4.2 Economics of Values

Theoretically, the circular economy transforms the building from a cost factor into a valuable warehouse whose residual value is intended to cover the dismantling costs. Practice often refutes this calculation: the high Swiss labour costs for selective dismantling and processing often exceed the material value of virgin material. A reused steel beam can be up to twice as expensive as a new one due to the testing and logistics costs (Interview C, item 63). In addition, storage costs are identified as a "massive cost driver" that can quickly neutralize ecological advantages (Interview A, item 85). This leads to the realization that Reuse often does not scale in a purely market economy without external regulators or idealistic builders.

4.3 Trust

Another contrast emerges when it comes to trust. While theory relies on technological solutions such as blockchain or the Digital Product Passport (DPP) to guarantee a

seamless "Chain of Custody" [10], practice relies on analogue mechanisms. The trust is primarily based on the physical "building materials report in hand" (Interview G, item 32) and the personal inspection. Trust is therefore not (yet) fully digitizable, since haptic testing ("stuck-the grip") is considered the last instance (Interview D, item 50).

5 Conclusions

This work analysed stakeholders' views on reused materials and components for the circular economy from a role-based perspective.

The research involved a systematic analysis of current market acceptance levels and a comprehensive identification of core barriers. By evaluating the role of component and scrap exchanges, the study mapped the landscape of material reuse—from historic quality and aesthetic value to logistical and perception-based hurdles.

The primary outcome is structured around three interconnected elements. It identifies that while salvaged materials often surpass new products in quality, market growth it currently hindered by logistical uncertainty and perception gaps. The interviews with ten Swiss key stakeholders provide insights into specific interventions for stakeholders and policymakers to bridge these gaps, transitioning component reuse from a niche concept to a mainstream industrial practice.

This outcome can feed into a Comprehensive Action Plan structured around seven interconnected components. For this, more work is needed and will be done in the coming months.

The study demonstrates that the transition to a circular construction industry requires a collaborative, strategic roadmap to overcome market barriers. The interviews with ten Swiss key stakeholders provide insights into specific interventions for stakeholders and policymakers to bridge these gaps, transitioning component reuse from a niche concept to a mainstream industrial practice. Implementing the proposed Action Plan requires more work to unlock the full ecological potential of building component reuse, and to provide a clear path forward for both component exchanges and the broader construction sector.

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14. newCPR: Regulation (EU) 2024/3110 marketing of construction products and repealing Regulation (EU) No 305/2011. https://eur-lex.europa.eu/eli/reg/2024/3110/oj/eng

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Cradle Based Circular Approach for the Implementation of Circularity Through Material and Product Passports

Antonella Violano[1(✉)], Roxana Georgiana Aenoai[1], Genesis Camila Cervantes Puma[2], and Luís Bragança[2]

[1] Department of Architecture and Industrial Design, University of Campania "Luigi Vanvitelli", 81031 Aversa, Italy
antonella.violano@unicampania.it

[2] ISISE, ARISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal

Abstract. Achieving European climate-neutrality goals requires adopting circular strategies that regenerate the life cycles of building materials. Within this framework, Environmental Design provides the conceptual and methodological foundation for integrating circularity into the early stages of architectural and technological design. According to this perspective, the contribution discusses a Cradle-Based approach (CBa) which, supported by Material and Product Passports, directs the design process towards the cradle of the next use cycle, thus overcoming a perspective limited solely to end-of-life considerations.

The theoretical and legislative framework analysis (European regulatory requirements for eco-friendly design, construction products, waste management, the principles of design for disassembly, LCA, Level(s)) is needed to guide the discussion about the CBa through a new cradle scenario-based analysis and scenario life cycle indicators of disassembly, recovery, durability, circularity, and environmental impact, made operational and traceable through Material and Product Passports. By embedding circular criteria and Material and Product Passports into Environmental Design processes, the method enables anticipation of material flow regeneration and guides informed design choices that reduce waste and emissions while supporting the transition towards more sustainable, adaptive and regenerative built environments.

Keywords: Cradle to Cradle · Circular Approach · Material and Product Passport · Circular Design · Environmental Design

1 Introduction

The transition of the European construction sector towards climate neutrality has become a central objective of the European Union's climate strategy. The built environment is a critical domain for achieving long term decarbonisation targets, in fact, the construction and operation of buildings account for approximately 37% of global energy-related CO_2 emissions and more than 1/3 of global material consumption [1]. These figures highlight the need to reconsider how buildings are designed, constructed, used, and ultimately dismantled.

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The construction sector traditionally follows a linear model in which the environmental strategies largely target end-of-life (EoL) stages. While these efforts reduce landfill waste, they are reactive and limit material preservation, hindering climate-neutrality and resource-efficiency goals [2].

The circular economy has become central in research and policy on the built environment. Circular construction focuses on keeping materials in productive cycles through design strategies for reversibility, adaptability, and recovery [3]. Buildings-as-material banks view buildings as temporary repositories of recoverable, reusable materials. Digital information systems play a crucial role in enabling this transition. In particular, Material and Product Passports (MPPs) have been proposed as documenting tools for improving traceability and transparency of information, to support circularity [4]. European initiatives promoted by the European Commission, including research programmes such as Buildings As Material Banks [5], have explored the role of material passports in supporting circular construction practices.

Despite these developments, most existing frameworks continue to treat the EoL stage primarily as a waste management issue rather than a design opportunity. Consequently, a gap remains between circular economy principles and the decision-making processes that shape building design [6]. To address this limitation, recent research has begun to explore a shift from EoL approaches towards a cradle-based perspective, in which the end of one lifecycle is conceived as the cradle of the next.

MPP supports scenario-based design to anticipate future material flows like reuse, refurbishment, remanufacturing, or recycling. Including these at the design stage helps create regenerative material cycles and increases long-term resource value.

This article explores the integration of a Cradle-Based approach (CBa) in architectural and engineering design, with a focus on the role of Material and Product Passports in supporting cradle-to-cradle transitions operations. This approach guides the design process toward the next material cycle, aiding the transition from linear to regenerative, circular building systems.

2 Methodology

This research adopts a design-oriented approach to develop and operationalise a CBa for circular transitions in the built environment. The proposed framework reframes the building as a dynamic material system, shifting the focus from conventional EoL management towards cradle-of-the-next-use-cycle thinking. Through scenario construction, the methodology explores regeneration pathways that extend material value across successive use cycles. European circular economy principles provide contextual boundary conditions, while MPPs are enabling tools for traceability, monitoring, and lifecycle continuity. The outcome is a conceptual methodological framework that translates circularity principles into a project-oriented design strategy for environmental design process.

Methodologically, the study follows a qualitative framework-analysis approach in two stages: **(1) regulatory and theoretical framework analysis**, identifying conceptual foundations and operational limitations of cradle-based lifecycle perspective, supporting the definition of key indicators to guide life cycles management; **(2) scenario-based analysis** in which potential scenarios and indicators are framed, combining disassemblability, recovery potential, durability, circularity performance, and environmental

impact metrics, into multicriteria scenario-based matrices, supported by MPPs, to ensure lifecycle traceability and monitoring (Fig. 1).

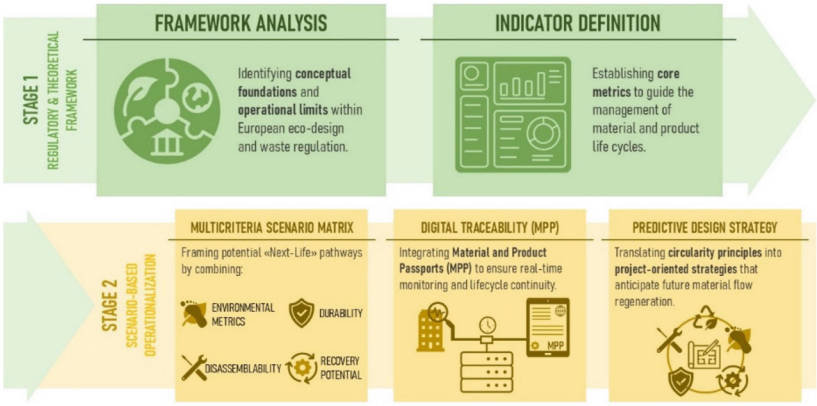


Fig. 1. The Cradle-based approach: a methodology for regenerative technological design

2.1 Research Design and Framework Development Approach

This study proposes a design framework to address the lack of operational models for regenerative lifecycle transitions in the built environment. The Cradle-Based Approach combines circular economy, lifecycle assessment, and circular design strategies to evaluate future material cycles early in the design phase. The framework is oriented towards the conceptualisation of indicators according to Design for Disassembly and Design for Recovery strategies, assessed through Life Cycle Assessment (LCA), which facilitate the future extraction and reintegration of materials into subsequent use cycles [7]. The development is guided by key European regulations and policies promoting circularity and digital traceability in construction, as Regulation (EU) 2024/1781 on Ecodesign, Regulation (EU) 2024/3110 on Construction Products, and Directive 2008/98/EC on waste. Additional guidance comes from the EU Construction and Demolition Waste Protocol and the Level(s) framework, which support lifecycle thinking and environmental assessments in building design.

The study's theoretical and regulatory framework was conducted through a structured review of key European legislative instruments and peer-reviewed literature (databases: Web of Science, Scopus), focusing on the last decade's research on lifecycle management, circular design strategies, and digital traceability in construction. Conceived as a conceptual framework analysis, it aimed at identifying recurring principles, operational variables and methodological gaps related to cradle-based circular design. The variables/criteria set (Sect. 2.2) was developed by mapping literature-derived variables against the functional requirements of each strategy within the 10Rs priority hierarchy [8]. This process was designed to be replicable: any research team can (1) identify applicable regulatory boundary conditions, (2) map material/component characteristics

against the 10Rs hierarchy, and (3) translating these into measurable indicators traceable via MPP data flows. While this work focuses on the conceptual operationalisation, its transferability across building typologies and regulatory contexts remains a priority for future empirical validation. Material and Product Passports act as digital infrastructures for data management, traceability, and lifecycle monitoring, documenting material traits, performance, and recovery potential, to support regeneration assessment and cradle-to-grave lifecycle thinking.

2.2 Scenario-Based Analysis

The cradle-based approach to the built environment's life cycle redefines the "End of Life" as "Next Life", by closing the cycle. The Design phase should adopt a predictive approach using scenario-based analysis to forecast the 'future lives" of elements, supported by tools like multi-criteria matrices and MPP, guiding lifecycle management toward predicted scenarios. The next "cradles" have been identified in the circular economy strategic framework, namely among the 10Rs of circularity, which focuses on "extending useful life": Reuse, Repair, Refurbish, Remanufacture, Repurpose, and finally High-quality Recycling.

Table 1. The fundamental variables that describe the potential access to new life scenarios.

Category	Variables/criteria	Description
Design and Assembly	Disassembly	Non-destructive disassembly level for recovery without physical damage [9].
	Connection Types	Mechanical connections or chemical bonds determine the separation difficulty and the element possible damage [9].
	Standardization	Reduced number of types of components to minimize the procedures risks [9].
	Accessibility	Ease access for maintenance or replacement without damaging surrounding elements [11].
Physical and Technical	Durability	Resist deterioration over time and wear and tear [11].
	Structural and mechanical integrity	Preservation level of the original properties (e.g., compressive strength or tensile strength) [14].

(*continued*)

Table 1. (*continued*)

Category	Variables/criteria	Description
	Maintainability and repairability	Components that can be maintained, repaired, or refurbished are more likely to extend their life cycle [13].
Chemical and Safety	Presence of toxic substances or contaminants	The presence of hazardous substances or chemical finishes can prevent their safe reuse or contaminate recycling streams [15].
	Material complexity and purity	For recycling, single-material solutions are preferable to complex composites, as separating different materials is often difficult and costly. Material purity is key to avoiding downcycling [16].

The order in which the scenarios are mentioned also represents, as stated by the scientific literature, a ranking according to their environmental impact in terms of emissions, energy and resource consumption [8], and this has also been taken as the order of priority of the 'new lives'. However, numerous variables determine an element's suitability for a given scenario. These must be translated into indicators describing the element's condition, enabling prediction of its potential future life. Table 1 summarises the identified variables.

Translating variables/criteria into measurable indicators enables creating scenario-based multi-criteria matrices to identify optimal new life scenarios. Indicator combinations define scenario access requirements, guiding design/management, while MPP data flows supports real-time, accurate access scenario updates [12].

3 Discussion

The proposed CBa aims to orient design frameworks towards predictive perspectives that outline next-use-cycle scenarios in advance, enabling proactive life-cycle management for closed-loop circularity. The shift from a reactive to a predictive design paradigm is fundamental, moving from damage management to value creation and regeneration, going beyond minimum cost/performance requirements and waste management, toward operational circularity integration with a regenerative purpose [10]. Table 2 compares the two paradigms.

The CBa offers unique contributions at the design methodology and lifecycle management interface compared to conventional methods. While existing LCA frameworks robustly quantify environmental impacts, they are generally used retrospectively as assessment tools rather than proactive tools for early-stage design decisions. Design for

Disassembly approaches address technical reversibility at component level but do not systematically link disassembly indicators to prospective use-cycle planning supported by dynamic digital tools [7]. The CBa integrates these complementary methodologies into a coherent, predictive design framework, shifting lifecycle thinking from retrospective evaluation to prospective generation, enabling design decisions that actively regenerate material value rather than merely minimising environmental losses. The goal is therefore to provide an approach based on Design for Disassembly and Design for Adaptability principles [11], orienting preliminary design towards strategies for reintroducing components into circular supply chains at the end of their life cycle, while broadening its scope by considering multiple possibilities to minimise unexpected events.

A scenario-based operational matrix is proposed as a support combining indicators with MPP data to predict the best life scenario at any stage. These matrices aid preliminary design and management by integrating environmental, technical, economic, and social factors. However, they need reliable data and high system interoperability (LCA-Digital Passports-BIM) to work effectively at scale [11].

MPPs are crucial for tracking the details and evolution of building components through dynamic indicators. However, barriers to adopting this predictive Cradle-Based approach include standardisation, digital interoperability, data access, and stakeholder participation [17]. The shift to this predictive CBa presents several notable operational challenges. The lack of standardised indicator protocols hinders cross-project comparisons and the adoption of multi-criteria matrices. Achieving digital interoperability between BIM, LCA tools, and MPP systems is complex and depends on developing sector-wide data standards. The framework is conceptual and its practical reliability needs to be tested using real case studies, which is a current limitation. Furthermore, engaging stakeholders across the supply chain is essential for data flows, yet coordination mechanisms for multi-actor lifecycle management are not well established.

Table 2. Comparison between reactive and predictive paradigms.

	Reactive	Predictive
Main goal	Meeting project brief, cost, performance and regulatory requirements, with possible "burden shifting" effects.	Maximise circularity and value retention across multiple use cycles; resource regeneration.
Life Cycle boundary	Often limited to partial lifecycle boundaries (e.g. Cradle to Gate or simplified Cradle-to-Grave approaches)	Cradle to Cradle
Circularity	Implemented as "beyond system boundary".	Central in lifecycle design and management.
Flux focus	Operational energy use and, in some cases, "upfront embodied carbon" assessment, limited material flux management.	Embodied and operational energy and carbon evaluation and management; material flux management.

(*continued*)

Table 2. (*continued*)

	Reactive	Predictive
MPP	Static approach and unclear data management.	Central use: complete data availability managed and updated dynamically during the lifecycle, supporting decision making.
Stakeholders	Gaps in stakeholders' communication during the life cycle, because of lack of clear and complete data and purposes.	Full cooperation thanks to completeness and interoperability of dynamically updated data and clear goals.
Design stage	Options chosen mainly on cost/performance; no life cycle planning.	Options selected on next-life scenario-based analysis and life cycle planning.
Operational stage	Static approach focused on energy use and basic reactive maintenance to manage the damage.	Dynamic approach focused on performance monitoring for efficiency and lifecycle management for circularity.
End of Life stage	Demolition and reactive waste management; low quality circular strategies implemented, decided during EoL stage.	No EoL, but New Life. Pre-planned strategies for no waste production, supported by lifecycle management through MPP.

4 Conclusions

The transition to climate-neutral, resource-efficient built environments demands shifting from linear to circular systems. This study proposes a CBa that treats the end of one material's use as the start of the next. By incorporating prediction into design, it aims to go beyond waste management, fostering material regeneration across use cycles. The proposed framework highlights the role of Environmental Design as a strategic entry point for integrating circularity at the early stages of architectural and technological design. Within this perspective, MPPs emerge as a key enabling infrastructure, supporting lifecycle continuity through improved data traceability, transparency and information sharing. By linking material characteristics, technical performance and environmental indicators to scenario-based design logic, these digital tools can contribute to more informed decision making and to the anticipation of potential future material trajectories such as reuse, refurbishment, remanufacturing or high-quality recycling. The study also introduces the conceptual structure of scenario-based multi criteria matrices that combine indicators related to disassembly potential, durability, recovery pathways, circularity performance and environmental impact. Although the present work focuses on the conceptual and methodological architecture of this framework, the proposed indicators and variables represent a first step towards operationalising predictive lifecycle management in the built environment. The originality of the approach lies in integrating circularity principles and MPPs into the environmental design process, reinterpreting MPPs as predictive

informational infrastructures supporting the anticipation of future 'next-life' scenarios during the early design stages. From this perspective, lifecycle information becomes an active driver of regenerative decision-making, rather than being limited to passive documentation for end-of-life management. Future research should focus on developing the multi-criteria matrices and defining measurable indicators for scenario evaluation in real design contexts. It should also explore integrating the framework with digital tools like BIM-based life cycle assessment systems and Material and Product Passport platforms. Applying the approach to real case studies is essential to test its feasibility and value for circular design and regenerative built environments.

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Transnational CDW Valorisation for Secondary Raw Materials: Technological, Economic and Social Perspectives

Berkan Kahvecioğlu[1(✉)], Fatma Seyma Keskin[2], Emine Özdoğru[3], Emircan Özçelikci[4,5], Yunus Emre Kaya[4], Mustafa Şahmaran[4], Semra Arslan Selçuk[1], Hüseyin İlcan[4], Diana Bajare[6], Tatjana Tambovceva[7], Janez Turk[8], Anja Kodrič[8], Alenka Mauko Pranjić[8], Stylianos Yiatros[9], Eirini Konstantinou[9], Anthi Charalambous[10], Meslec Mihaela[11], Haase Matthias[11], Martina Hefele[11], Heinz Bernegger[12], Katerina Tsikaloudaki[13], Raluca Buzatu[14], Viorel Ungureanu[14], Janno Torop[15], Cansu Özcan Kilcan[15], and Alan H. Tkaczyk[15]

[1] Department of Architecture, Gazi University, Ankara, Türkiye
fskeskin@mehmetakif.edu.tr
[2] Department of Architecture, Burdur Mehmet Akif Ersoy University, Burdur, Türkiye
[3] Civil Engineering Department, Ankara University, Ankara, Türkiye
[4] Civil Engineering Department, Hacettepe University, Ankara, Türkiye
[5] Civil Engineering Department, Ankara Yıldırım Beyazıt University, Ankara, Türkiye
[6] Institute of Sustainable Building Material and Engineering Systems, Faculty of Civil and Mechanical Engineering, Riga Technical University, Riga, Latvia
[7] Governance and Security Institute, Riga Technical University, Riga, Latvia
[8] Slovenian National Building and Civil Engineering Institute, Dimičeva ulica 12, 1000 Ljubljana, Slovenia
[9] Department of Civil Engineering & Geomatics, Cyprus University of Technology, Limassol, Cyprus
[10] KyklOIKOdromio, Nicosia, Cyprus
[11] ZHAW Zurich University of Applied Sciences, Wädenswil, Switzerland
[12] SGNI, Zurich, Switzerland
[13] Aristotle University of Thessaloniki, Thessaloniki, Greece
[14] Faculty of Civil Engineering, Politehnica University Timisoara, Timisoara, Romania
[15] Institute of Technology, University of Tartu, Tartu, Estonia

Abstract. Construction and Demolition Waste (CDW) represents a key barrier and opportunity in advancing circularity within the built environment, as countries intensify efforts to reduce waste and recover resources more effectively. Its valorisation increasingly relies on the combined influence of technological capabilities, economic feasibility and social acceptance. This study brings together national data from eight countries: Cyprus, Estonia, Greece, Latvia, Romania, Slovenia, Switzerland, and Türkiye to explore how economic, technological and social perceptions shape the potential of CDW in circular construction. The analysis examines the main economic opportunities and challenges in CDW recycling, including national market gaps and the availability of certified CDW-based products. It also highlights the growing role of digital tools, such as material-tracking systems,

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which support more reliable and transparent reuse pathways. From a social perspective, public perceptions and user preferences regarding recycled materials are analysed, along with stakeholder roles across the CDW value chain and the social implications of waste management. The study shows that an integrated approach that combines economic incentives, digital technologies, and stakeholder and community participation can effectively transform CDW into a valuable secondary raw material. It aims to guide policymakers, local governments, and industry professionals in creating diverse, practical initiatives from a comprehensive perspective, while also helping establish a strategic waste management framework.

Keywords: Construction and Demolition Waste (CDW) · Circular Construction · Secondary Raw Materials · CDW Valorisation · Digitalisation in Construction

1 Introduction

Construction and Demolition Waste (CDW) is one of the key material streams in the global transition toward a circular economy. With urbanisation, infrastructure development, and growth in the building stock, the amount of waste generated by construction activities will also increase. Therefore, this situation is transforming into a large consumption sector that uses primary raw materials [1]. In total waste statistics at the European Union, more than a third comes from CDW -over about 925 million tons per year- highly heterogeneous both in mineral and non-mineral content: concrete, bricks, metals, wood, glass, plastics [2]. Consequently, the management of CDW is of strategic importance due to its scale, material density, and environmental footprint. CDW is now increasingly conceptualised as a secondary raw material within broader systems of circular construction. The shift is associated with the transformation of linear "take–make–dispose" models into more resource-efficient modes that include waste prevention, reuse, and high-quality recycling, parallel to the gradual mainstreaming of circular economy discourse [3]. Despite increasing awareness of the problems related to CDW, fragmented policies, technological limitations, economic deterrents, and societal acceptance barriers remain a challenge for countries.

Most existing studies on CDW management evaluate single dimensions, predominantly emphasising technological and economic analyses [4, 5]. Increasing evidence in recent years shows that economic conditions - infrastructure, both digital and physical, and societal-level governance models and behavioural norms - play a key role in enabling or constraining technological readiness and cost-competitiveness pathways to successful CDW valorisation. This paper is therefore framed within an integrated, cross-country perspective, evaluating the economic, technological, and social dimensions and interactions that drive or hamper the valorisation of CDW. Eight countries (Cyprus, Estonia, Greece, Latvia, Romania, Slovenia, Switzerland, and Türkiye) from dıverse geographical contexts, with emerging to mature markets and under different governance structures, were selected. The study will evaluate national experiences to capture common and shared trends, enabling factors, and obstacles in transforming CDW from an assumed problem into a secondary raw material.

This study aims to address gaps in the literature by expanding the limited economic and technological perspectives on CDW through social and stakeholder engagement and by conducting an international synthesis. In line with this objective, the main research question guiding the evaluation is: How do economic and technological conditions, along with social acceptance and stakeholder perceptions, shape CDW valorisation within the circular construction context? By addressing this question, the paper contributes to a growing body of literature advocating multidimensional, governance-oriented approaches to implementing the circular economy in the built environment.

2 Method

The study uses a multi-country research design to analyse the economic, technological, and social aspects of CDW valorisation in circular construction systems. Eight countries - Cyprus, Estonia, Greece, Latvia, Romania, Slovenia, Switzerland, and Türkiye - were selected to represent diverse geographical regions and various levels of economic development, with different governance structures, spanning emerging to fully developed waste management and recycling markets. Such diversity allows both an analysis of how very different institutional/regulatory/market environments shape paths for CDW valorisation and the discovery of common challenges across national contexts, as well as potentially transferable practices.

Data were collected by systematically reviewing national statistics and official policy documents, strategic plans, regulatory frameworks, and publicly available reports on CDW management and circular economy implementation in construction practices. The resource selection focuses on documents that address direct CDW, recycling, digitalization, and circular construction practices. To ensure data consistency, the data collected using the same thematic coding structure were evaluated: economic conditions, technological/digital enablers, and social perceptions. The evaluation incorporated stakeholders' roles within a cross-country comparative synthesis, aiming to identify emerging common themes and structural gaps across enabling factors, while retaining sensitivity to country-specific contexts. The thematic comparative approach (inductive) allows for the discovery of both widespread regularities and context-dependent dynamics (interaction effects), thus providing a strong intellectual footing for developing fine-grained yet practically relevant (hence evidence-based) recommendations. The study is limited by the fact that CDW levels vary across countries and are based on national data sources. Therefore, the findings should be interpreted as a comparative thematic synthesis rather than a statistically definitive assessment.

3 Economic Perspectives on CDW Valorisation

The reuse of CDW as a secondary raw material brings wide economic benefits, particularly within circular construction systems. National strategies, policy assessments, and market analyses demonstrate that, in addition to reducing waste, the recovery of CDW creates jobs in the country's labour market, develops local markets, and improves resource-use efficiency in construction value chains. Enterprise support schemes further

illustrate the effects of incipient market formation: national circular economy de minimis programs have financed dozens of projects and created new jobs, thus registering growing economic activity related to CDW valorisation [6, 7].

Evidence from each country shows distinct yet parallel benefits. In relatively advanced CDW markets such as Romania, Greece, and Slovenia, government programs, circular economy plans, and green public procurement practices play a significant role in both supplying and using CDW [8–11]. These measures facilitate greater use of recycled materials in construction and expand recycling systems [12, 13]. On the other hand, in growing markets such as Türkiye, Cyprus, Estonia, and Latvia, using CDW mainly creates jobs in areas including landfill management, road construction, landscaping, infrastructure development, and local recycling businesses [14–17]. Despite differences in scale and implementation difficulty, the basic economic reasoning remains strong: using CDW reduces dependence on imported materials, supports local supply chains, and adds value by keeping resources within national and regional economies.

Data from each country shows similar gaps and shared challenges. In Romania and Greece, even though governments set rules and technical standards, the use of recycled materials remains low. This can be attributed to several factors, including lower costs of new construction materials, limited high-quality data, uncertainties about implementing such changes, and persistent concerns about the quality of recycled products [18–20]. In Türkiye, Cyprus, Slovenia, and Latvia, the main challenges are associated with certification procedures for materials, difficulties in recruiting skilled labour, the high costs of processing and transporting materials, and insufficient demand or support from businesses purchasing these materials [15, 21–23]. Unless there is a cohesive economic strategy that integrates the establishment of common standards, improvements in certification processes, financial incentives, and the enhancement of trust within the market, recycling of CDW is likely to remain economically unviable and inefficient, even with current technological capabilities.

4 Technological Perspectives on CDW Valorisation

Even though the level of development and use of digital tools (DT) varies from country to country, they are becoming essential in circular CDW management. Tools like Building Information Modelling (BIM), artificial intelligence (AI), material passports, and digital tracking systems help make better decisions, identify which parts to remove, recover materials, and recycle them properly [24, 25]. Common trends in the countries studied show a preference for DT in the processing and CDW.

In Romania, progress is reflected in increased institutional attention to digitalisation, including the development of a national BIM roadmap and initiatives to strengthen digital skills in the construction sector. Implementations at the project level include Scan-to-BIM workflows using laser scanning and photogrammetry as well as pilot initiatives exploring AI- and sensor-assisted CDW sorting, such as Robot Efficient Cdw Intelligent Classifier for Automatic Recycling Management (RECICLARM) [26, 27]. Slovenia's CINDERELA project presents a digitally integrated circular business model for a one-stop-shop platform marketplace for stakeholders in the waste-to-resource value chain. Latvia LIFE "Waste to Resources" provides easily accessible information and an

actual citizen engagement platform that supports circular economy practices through digital dissemination and the development of local repair and recycling infrastructure. Switzerland has developed digital solutions such as "Madaster" and "buildingSMART", both with a strong focus on technology [28]. Greece is a participant in the RECONMATIC project, which will develop automated, digital, and robotic solutions to support collaboration among construction industry stakeholders and improve waste traceability [29].

Digitalisation efforts in Türkiye and Cyprus are shaped more by governance structures and regulatory practices than by advanced automation. Cyprus provides a notable example of operational digital traceability through its mandatory collective systems and the Electronic Waste Recording System [30]. In Türkiye, digitalisation efforts primarily focus on electronic monitoring and reporting mechanisms, exemplified by systems such as the Electronic Concrete Monitoring System (ECMS). In parallel, the emerging consideration of AI-based tools for post-disaster damage assessment indicates a growing potential to support future evaluation and management of CDW [31, 32]. Although digital CDW technologies are not yet mature, their broad use is considered essential.

5 Social Perspective, Public Perceptions, and Stakeholder Roles on CDW Valorisation

A comparative social perspective on CDW valorisation indicates that, across countries, public acceptance and stakeholder engagement are influenced less by general environmental awareness than by tangible institutional, economic, and regulatory frameworks. Despite variations in governance structures and market maturity, the evidence consistently suggests that trust in certified quality standards, affordability, and clearly defined stakeholder responsibilities plays a decisive role in normalising reused and recycled construction materials within mainstream construction practices.

In Romania, consumer and stakeholder perceptions are strongly influenced by price- and quality-considerations; surveys indicate a cautiously positive yet conditional acceptance of reused and recycled materials, with 73% of buyers favouring certified "green" products, while demonstrating limited willingness to pay a premium [33, 34]. Evidence from the RECONMATIC Project suggests that technical familiarity and workflow reliability dominate decision-making over sustainability motivations, positioning Greece at an early stage in the social normalisation of CDW valorisation [35]. In Slovenia, while environmental awareness is increasing, scepticism about the quality and safety of recycled construction materials persists, but awareness is being raised through EU-funded projects [36].

In Cyprus, stakeholder surveys conducted under the Build CIRCULAR Up project show that 65% of construction actors actively separate CDW and derive economic benefits from selling recycled materials, despite gaps in standards, infrastructure, and cross–supply-chain collaboration [37]. In Türkiye, academic and stakeholder studies report broadly positive attitudes among users, designers, and professionals toward recycled and reusable materials, particularly regarding environmental benefits and design potential [38]. Public perception in Estonia (as well as in the Nordics) is mixed and largely characterised by a lack of awareness [39]. Similarly, in Latvia, the public lacks sufficient

knowledge of circular construction principles, identifying insufficient information and awareness as a primary societal barrier to the adoption of circularity [40]. Collectively, these cases demonstrate that while social receptivity exists across contexts, its consolidation depends on aligning awareness with enforceable regulations, credible quality assurance systems, and tangible economic benefits.

6 Conclusions and Recommendations

This study demonstrates that utilising CDW as a secondary raw material is a multidimensional process shaped not only by economic and technological capacity but also by re gulatory alignment and societal dynamics. Evidence from eight countries highlights the significant potential to increase recycling capacity through technological innovation, particularly through improved sorting, monitoring, and material recovery systems. Economic instruments (especially green public procurement, certification schemes, and incentives) play a decisive role in shaping viable markets for CDW-derived products. The finding further confirms that social acceptance is influenced not solely by environmental awareness but by pricing structures, regulatory clarity, and clearly defined stakeholder responsibilities (Table 1).

Table 1. Comparative Patterns in CDW Valorisation Across Countries

Country	Economic	Digitalisation	Social	Main Barrier	Key Enabler
Romania	◆◆◆◆◇	◆◆◆◇◇	◆◆◆◇◇	Market trust	Green procurement
Greece	◆◆◆◆◇	◆◆◆◇◇	◆◆◆◇◇	Cost competition	Policy frameworks
Slovenia	◆◆◆◆◆	◆◆◆◆◆	◆◆◆◇◇	Quality perception	Circular platforms
Türkiye	◆◆◇◇◇	◆◆◇◇◇	◆◆◆◇◇	Digital gaps	Regulatory transition
Latvia	◆◆◇◇◇	◆◆◇◇◇	◆◆◇◇◇	Knowledge gaps	EU initiatives
Cyprus	◆◆◇◇◇	◆◆◆◇◇	◆◆◆◇◇	Infrastructure	Digital traceability
Estonia	◆◆◆◇◇	◆◆◆◇◇	◆◆◇◇◇	Public engagement	Digital governance
Switzerland	◆◆◆◆◆	◆◆◆◆◆	◆◆◆◇◇	Public engagement	Advanced digital systems

Comparative findings indicate that a successful CDW evaluation depends on the alignment of the following three dimensions: (i) economic incentives and market stability, (ii) digital and technological traceability systems, and (iii) social trust supported by regulatory legitimacy and stakeholder coordination. Based on these findings, the study

recommends adopting a multi-faceted approach that simultaneously addresses economic, technological, and social dimensions through coordinated policy action. Finally, future research should expand this cross-country synthesis by incorporating empirical data and long-term assessments to better analyse the impacts of governance reforms and digital innovation on circular construction systems.

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Integrating Circular Objectives into Performance-Based Façade Technical Specifications: A Conceptual Framework

Marie Belle Georges(✉) and Issam Srour

Department of Civil and Environmental Engineering, American University of Beirut, Beirut, Lebanon
msg20@mail.aub.edu

Abstract. Façade systems are typically designed using performance-based criteria such as structural capacity, weather protection, thermal performance and energy efficiency. These documents are conventionally used by façade stakeholders to define how façade systems are designed and delivered. Circular considerations, however, are rarely written as explicit façade requirements. Reuse and design for disassembly are often discussed during design but are not al-ways translated into specification clauses. This paper explores how circular objectives could be incorporated into façade delivery through performance-based specifications. Circular economy frameworks and façade literature were reviewed, together with the structure commonly used in façade technical specifications. The review highlighted several circular objectives relevant to façade systems. These include design for disassembly, reuse potential and maintainability. Other aspects such as adaptability, service life alignment and material traceability were also identified. The study then explores how these ideas could be reflected in façade specifications. In a project specification, they would appear in different sections of the document. Some relate to material information submitted by the contractor, while others concern design details that allow components to be disassembled or maintained. Compliance could be checked through design submissions, contractor submittals or inspection during installation. If circular provisions are written into façade specifications, they become part of the project requirements rather than general sustainability intentions. Contractors and designers would then need to address these objectives during façade design and construction.

Keywords: Façade engineering · Circular economy · Performance-based specifications · Building envelopes · Circular construction

1 Introduction

Façade systems are essential in the performance of buildings [1, 2]. They are the interface between the interior and exterior environment [1]. The façade design is dictated by performance-based technical specifications that establish requirements for structural behavior, thermal performance, watertightness, airtightness, fire safety and acoustic performance [2, 3]. The specifications define the façade requirements, how compliance is verified, and the responsibilities of project stakeholders [3].

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Circularity has become commonly discussed in the built environment sector [4, 5]. Concepts such as design for disassembly, material traceability and service life extension are now conferred more frequently in relation to building components [6, 7]. However, these ideas are typically addressed at building assessment level rather than within the technical structure of façade specifications.

Despite the growing attention to circularity, it is not consistently and commonly expressed within façade technical specifications. In many projects, circularity is addressed through certification systems or sustainability reporting rather than through façade specifications' clauses. This study explores where circular objectives could be placed within façade performance-based specifications.

2 Literature Review

2.1 Circularity in the Built Environment

The built environment sector is a major consumer of materials and a significant source of construction waste. In response, circular economy principles have been increasingly discussed as a way to address these challenges [4, 5, 8, 9]. Circularity in construction encompasses several approaches, from the reuse of construction materials to the recycling of construction and demolition waste (CDW) [4, 5]. These approaches also include extending the life of materials and designing buildings so that components can be reused later [4, 6]. Buildings contain large quantities of materials. For this reason, building components play an important role in enabling circularity.

2.2 Circularity in Façade Systems

Building façades represent a significant part of a building. They also contain large quantities of different materials such as glass, aluminium, steel, gaskets and sealants [2]. Façade systems may be replaced or refurbished during the life of a building, often before the service life of the main structure [7, 10]. This creates opportunities to consider circular strategies at the façade level. Many of these materials eventually become construction waste. For this reason, façades are relevant when discussing circularity in the built environment. Several studies have examined circular approaches for building façades. Commonly discussed ideas include design for disassembly, reuse of façade components, material traceability or material passports, and service life considerations [6, 7, 10–12]. However, these ideas are usually discussed at the building level rather than within façade specifications documents.

2.3 Performance-Based Façade Specifications

The façade technical specifications sets out the performance criteria that the façade system must comply with [2, 3]. These requirements typically include structural performance, watertightness, airtightness, thermal performance, acoustic performance, fire resistance and durability. These specifications define compliance requirements, guide design development, allocate responsibilities between stakeholders and define what contractors must deliver.

2.4 Research Gap

Circular strategies for buildings and façade systems have been widely discussed. However, their integration into façade technical specifications has received limited attention. Circular ideas are not widely structured in façade technical specifications as performance criteria comparable to other façade requirements. This gap is noticeable. The paper considers how circular objectives could be incorporated into façade performance-based specifications.

3 Methodology

The methodology builds on reviewing three relevant frameworks related to circularity, examining the typical structure of façade technical specifications and analyzing literature review on circularity in façades. The proposed positioning was discussed informally with experienced façade professionals to assess practical relevance. The study adopts a qualitative and exploratory conceptual approach.

ISO 59020:2024 "Circular economy - Measuring and Assessing Circularity Performance" was reviewed due to its importance in providing a structured approach for measuring and assessing circularity performance across systems [13]. This international standard translates circular economy principles into defined indicators, lifecycle boundaries, measurement logic and performance evaluation structure. Since façade specifications are based on measurable performance requirements, ISO 59020 helps show that circularity can also be framed in measurable terms.

Level(s) - A Common EU Framework of Core Sustainability Indicators of Office and Residential Buildings (2021) was analysed because it shows how circularity is structured at the building assessment level [14]. Hence, in order to position circular provisions in façade technical specifications, it is important to understand how they are already structured elsewhere at the building level. This framework explicitly references adaptability and design for deconstruction. It frames circularity in terms of lifecycle performance, not just environmental intention. Circularity is not just a concept. It can be broken into structured requirements. Its relevance is in demonstrating how circular requirements could be organized and categorized systematically.

BREEAM New Construction Version 7 was also reviewed. This widely recognized sustainability certification system used to evaluate the environmental performance of buildings gives credits for lifecycle assessment, material documentation, and waste reduction [15]. This means circularity is already influencing how buildings are designed and evaluated. But these requirements usually sit in sustainability assessment systems. They are not always written directly into façade technical specifications.

Façade technical specifications follow a structured format. Similar to the general construction specification practice. The commonly used three-part structure; General Requirements, Products and Execution was examined to understand how these documents are organized. As well as the type of information typically belongs in each section. This was necessary in order to determine where circular provisions could realistically be placed.

The circularity objectives themselves were identified from recurring themes across the reviewed frameworks and literature. Only those considered relevant to façade specifications practice were retained. The positioning was then carried out against the three-part structure that underpins most façade technical documentations.

The proposed placement was also discussed informally with senior façade practitioners to see if it aligns with current practice. These were informal conversations rather than structured interviews. The paper is conceptual in nature and does not analyze data from specific projects.

4 Conceptual Framework

Performance-based façade specifications encompass the criteria required to design and deliver a façade system. In practice, façade specifications normally address issues such as structural capacity, thermal performance, resistance to water and air penetration, acoustic control, fire safety and durability. In practice, such requirements are not left at a conceptual level. They are translated into performance measurement criteria that can be tested, certified or verified through documentation.

From this perspective, circularity should be treated similarly. It does not always have to be addressed as an independent sustainability aspiration. Instead, circularity could be specified as other performance expectation. In terms of positioning, circularity requirements can potentially be placed in the same specifications' logic as structural capacity or thermal performance.

Figure 1 illustrates the conceptual relationship between circular objectives and the structure of façade technical specifications. Table 1 then shows where these objectives could be placed within the specification structure. The idea is not to propose a new specifications format. The intention is to demonstrate that circularity provisions could be incorporated into the typical façade performance-based technical specifications. Whether they follow a standard format or are written specifically for a project. By placing circularity within the façade technical specifications, it becomes part of the contractual performance requirements instead of remaining a separate sustainability target.

The wording in Table 1 simply shows where circular objectives could be placed in façade specifications. In practice these requirements would be reflected in different parts of the document. Some relate to material information submitted by the contractor. While others relate to design details that allow components to be disassembled or maintained. Compliance could then be checked through typical project practices such as design documentation, contractor submittals and site inspection.

Table 1. Conceptual positioning of circularity objectives within façade specifications' structure.

Circularity objective	Lifecycle phase	Specifications section	Possible specifications provision	Example
Design for disassembly	Design/End-of-life	Part 1 – Performance requirements	Allow disassembly of primary façade components without irreversible damage	Curtain wall panels fixed with bolted connections
Material traceability	Across lifecycle stages	Part 1 – Submittals	Documentation of material composition, origin and environmental data	EPDs and aluminium alloy information
Maintainability	Operation/service life	Part 3 – Execution	Components expected to require replacement remain accessible for maintenance	Glass units replaced without removing mullions
Reuse potential	Design/post-disassembly	Part 2 – Products	Preserve structural and functional integrity of reusable components	Standardized façade modules sized for reuse
Adaptability	Design/mid-life modification	Part 2 – Products	Allow future upgrade or modification of façade components	Glazing upgraded without replacing the frame
Service life alignment	Design stage	Part 1 – Performance requirements	Allow elements with different lifespans to be replaced independently	Gaskets replaced without removing framing

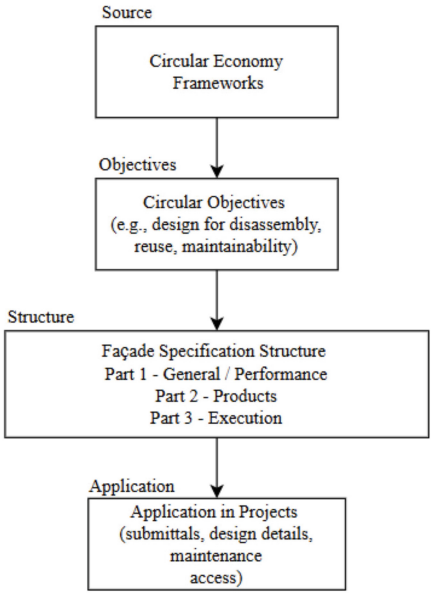


Fig. 1. Conceptual framework linking circular economy objectives with façade specification structure

5 Illustrative Application of the Framework

Table 2 presents examples of incorporating circularity objectives into performance-based façade technical specifications using conventional requirements typically found in façade projects. The examples show how circularity considerations can be included within current specification practices while maintaining the existing performance-based approach used in the façade industry.

Table 2. Examples of Integrating Circular Objectives into Performance-Based Façade Specifications.

Specification requirement	Circular objective	Example specification clause
Thermal performance requirements	Adaptability over service life	The façade system shall permit future replacement or upgrading of insulated glazing units without replacement of the primary framing system
Structural performance requirements	Design for disassembly	Mechanical fixings shall be utilized for primary facade components where possible to support future disassembly and material recovery

(*continued*)

Table 2. (*continued*)

Specification requirement	Circular objective	Example specification clause
Material selection requirements	Material traceability	To support future recovery and reuse, aluminum components shall include material identification and recycling information
Maintenance requirements	Maintainability	Damaged glazing components and gaskets shall be replaced without significant removal of adjacent façade elements

6 Discussion & Conclusion

When circular objectives are written into façade technical specifications, they become part of what must be delivered on a project. This changes their role. Specifications describe the roles of consultants, suppliers and contractors and explain how compliance is checked on a project. If circular provisions are written into these documents, they become part of what contractors must deliver. This influences material selection and procurement decisions, and it also impacts the preparation of technical submittals. Ideally, on projects the façade consultant and design team would include these requirements in the specifications. The contractors would address these requirements during tendering and construction phases. Circularity becomes part of the technical scope rather than considered only through certification schemes.

Market conditions and client priorities vary, which may limit the applicability of this approach across façade projects. Public developments could adopt such provisions more than smaller private projects. The conceptual framework presented here does not analyze real project specifications. Also, challenges such as cost implications or enforceability were not examined.

Circular objectives can be incorporated into the current structure of façade performance-based specifications. These provisions include design for disassembly and reuse potential. Other aspects relate to maintainability, adaptability, service life alignment and material traceability. The framework should therefore be viewed as an initial step rather than a complete solution. Future work could explore how similar provisions might be implemented in real project specifications.

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Disclaimer. During the preparation of this work, the author(s) used ChatGPT to improve the language and readability of some paragraphs in the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article

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Adaptability Potential Assessment Models: A Critical Review

Keziah Noxolo[1(✉)], Thomas Hesslenberg[2], Ben Holmes[2], Helen Fairclough[1], and Danielle Densley Tingley[1]

[1] School of Mechanical, Aerospace and Civil Engineering, The University of Sheffield, Western Bank, Sheffield S10 2TN, UK
kanoxolo1@sheffield.ac.uk

[2] Elliott Wood Partnership Limited, Society Building, 55 Whitfield Street, London W1T 4AH, UK

Abstract. The construction industry is applying more circular economy principles to reduce waste, raw material extraction and support decarbonisation goals. This changing landscape has led to developers considering adaptive reuse and building retention more seriously. However, the sustainability assessment models created to assess reuse potential are underutilised in industry, and there are a lack of studies analysing and contrasting existing approaches against one another in practice or applying different models to case studies to ascertain the different assessment outcomes. This study critically analyses various models, chosen from a semi-systematic review, evaluating the parameters used within the model and the calculation methodology. Structural appraisal reports and publicly available information from a number of adaptively reused buildings were used to assess the outputs of the models, comparing the outcome to what happened in reality. The results show the need for a more comprehensive and robust model that can adapt to a range of use types. New models should: (1) be interactive tools, to allow for filtering questions for specific use types; (2) be split into technical and non-technical questions to allow them to be used by experts and non-experts; (3) assess practical adaptive reuse potential and social wants separately to prevent bias affecting the final score; and (4) provide tangible recommendations to users, to make the models more valuable to single building developers.

Keywords: Adaptive reuse case studies · Adaptability assessment models · Circularity · Buildings

1 Introduction

New planning policies, such as Westminster's Retrofit First policy [1], are showing the shift towards adaptive reuse being considered more seriously in the construction industry. However, there is often reluctance to use this option due to a lack of information on the building [2], and a lack of knowledge about circularity [3]. One of the ways to mitigate this is to use assessment models that can quickly assess a building's adaptive reuse potential. Previous work comparing adaptability assessment models [4] looks only at

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how the current models are structured, rather than their usability and reliability, which is the knowledge gap that this paper fills.

1.1 Definition of Adaptive Reuse

There is a lack of consensus regarding an exact definition of *adaptive reuse*, however, for this study, it was important to define *adaptive reuse* to contextualise which models are within scope.

A small-scale review of definitions for *adaptive reuse* in literature led to the following definition, based on Schmidt III et al.'s [5] work on adaptability strategies and Brand's [6] building layers:

> Adaptive reuse refers to the infrequent, non-cyclical change to an existing building, either through change of function, which includes changes to the space, service or skin; or change of size, which includes changes to the space, service, skin or structure.

Change of function refers to the use of the building, either through change of use or to suit new requirements within an existing use. Change of size refers to the physical size of the building, achieved by providing additional floor space, either vertically or horizontally.

2 Methodology

2.1 Selection of Models

Throughout this paper, all assessment frameworks, instruments, methods, strategies and models will be referred to as assessment models. The adaptability potential assessment models were chosen through a semi-systematic review. First, Web of Science and Scopus were searched with the terms [adaptive reuse AND model AND assessment AND buildings].

A manual check of each paper was conducted to highlight only those that proposed new adaptability potential assessment models for existing buildings. This removed papers that aimed to: (1) Assess the effectiveness of past reuse schemes; (2) Focus on the delivery of reuse projects; (3) Assess the adaptability of proposed new-builds.

One model required input from several users to be used, which is beyond the scope of this study, so was removed from the analysis. This led to 6 models being identified.

From these models, references and citations were checked to identify other adaptability potential models. This led to a total of 9 models selected for this study.

2.2 Introduction of Case Studies

Each model was assessed using four UK-based case studies. The study was conducted using data from structural appraisal reports and publicly available information, in line with what would have been known prior to the reuse project occurring. Table 1 shows basic information about the existing buildings in their pre-reuse state. All four of the

case studies have recently undergone an adaptive reuse project, in line with the definition set out above, with the new and previous use type being office in all cases.

Table 1. Basic information about the case studies.

	A	B	C	D
General Location	London	London	London	Milton Keynes
Year of original construction	1840	2000	1920	1990s
Current Use Type	Office and Retail	Office	Office (Originally warehouse)	Office and Storage
Main Frame Type	Cast iron, steel and load- bearing masonry	Steel frame	Loadbearing masonry, and steel and iron columns	Concrete frame
Condition of Building (Pre-Strip Out)	No visible damage	Good	Poor condition of roof and slabs	Good
Storeys	5 (inc. basement)	6 (inc. partial basement)	2	6 (inc. basement)
Approx. floor space (m^2)	10,000	12,000	2,000	29,000

3 Critique of Approaches

This paper focuses on the different approaches the models use to calculate adaptability potential. For the individual parameters used in each model, we refer readers to the original papers. Table 2 shows the approaches each model uses.

Table 2. Approaches used by models.

	Knowledge Level	Use Type	Scoring	Output	Parameters
	Expert?	General?	User?	Categorical?	Only Physical?
TMOB [7]	×	×, Offices	×	✓	×
ARP [8]	×	✓	✓	×	×
iconCUR [9]	✓	✓	✓	✓	×
PAAM [10]	×	×, Offices	×	✓	×

(*continued*)

Table 2. (*continued*)

	Knowledge Level	Use Type	Scoring	Output	Parameters
	Expert?	General?	User?	Categorical?	Only Physical?
adaptSTAR [11]	✓	✓	✓	✓	×
Flex 4.0 (General) [12]	✓	✓	×	✓	✓
Flex 4.0 (Specific) [12]	✓	×, Offices and Schools	×	✓	✓
QACCB [13]	✓	✓	×	×	✓
Ozler and Gucyeter [14]	×	✓	×	×	✓
Total Yes (out of 9)	5	6	3	6	4

3.1 Knowledge Level of User

Some models required specialised knowledge, such as understanding the structure's condition and the impact this has on adaptability, and thus needed an expert to be used (5/9). Others only required general knowledge about the building and could be used by a non-expert (4/9). The expert models would require a design team's input, increasing costs to the owner and likely requiring a structural appraisal report, which may not be completed before the *Preparation and Briefing* stage (RIBA stage 1). The nonexpert models could be used at the *Strategic Definition* stage (RIBA stage 0) by the owner, making them more accessible. However, they did not look at the condition of the structure, whereas the expert models gave a deeper understanding of the physical building's adaptability potential.

3.2 Applicability to Different Use Types

Although most of the models applied to all current use types (6/9), a few were limited to specific uses (3/9). Non-specific models can be used for a wider range of buildings; however, they do not allow for as in-depth questions, as certain criteria would only apply to particular use types, for example, office grade would only apply to office buildings. Specific models allowed for more in-depth questions.

3.3 User or Criteria Scoring

The models used two different scoring methods: User-scored (3/9), which required the user to score how adaptable different building attributes were on a scale; and criteria-based scoring (6/9), which gave the user a set amount of options to choose from for

each parameter. Criteria-based models were quicker to use, but only when the building attribute fit into one of the pre-assigned categories, otherwise, it was challenging to assign a score. The user-based scoring was applicable to all building typologies, however, it requires the user to understand what makes a building more adaptable. It can also lead to bias if the user deems certain building attributes as more adaptable, allowing the model to be misused to fit a certain agenda.

3.4 Final Score and Output

The majority of the models (6/9) gave the user a categorical final score, such as an adaptability class, while the others' (3/9) output was purely numerical, only giving a score or percentage. While the numerical score can be used to compare several buildings, they are less useful when looking at individual buildings, as they don't translate a score into a level of adaptability. On the other hand, the categorical scores work for both individual buildings and comparing buildings; however, the classes are often split equally, which may not reflect reality, for example, the adaptability of a building may be exponentially related to the score.

3.5 Types of Parameters Included

Some models only included physical parameters (4/9), such as the structure, condition and layout of the building. Others included a wider range of parameters (5/9), for example, the social value of the building, such as user satisfaction and community support. Models that only included physical parameters were fairly objective, so there was less confusion; however, the model cannot assess if reusing the building would lead to any added value, economic or social. On the other hand, including non-physical parameters meant that the model could evaluate whether reuse has any value, but the non-physical parameters are often subjective and harder to measure; for example, user satisfaction requires interviews, which would be time-consuming to obtain.

4 Critique of Results

Although none of the models found that the buildings were not adaptable, there was variation in the magnitude of adaptability they predicted, see Fig. 1. This discrepancy may be due to the models looking at adaptability from different lenses, such as some focusing more on social wants than others. The models that only looked at physical factors scored lower than those that also considered other factors.

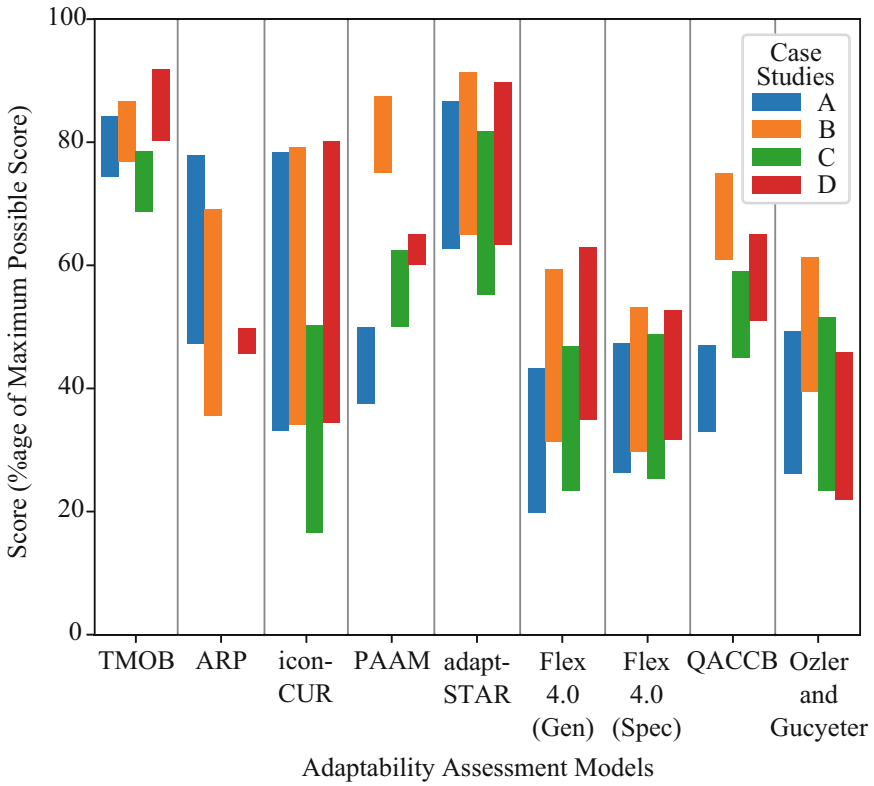


Fig. 1. A figure showing the model results for all four case studies. A higher percentage represents a more adaptable building. The coloured ranges represent the spread between the most conservative and most optimistic assumptions for unknown parameters.

The four case studies are located in authorities with policies dissuading the net loss of office space, and therefore would be considered to be in" priority area[s]" [7]. This means that they should not be changed to residential and, therefore, would fail the initial filtering criteria in the TMOB model [7]. However, the assessment was continued for full evaluation to test the validity of the model. The ARP model [8] is incompatible for buildings that are significantly older than their typical design life, which is the case for case study C, resulting in a negative percentage, and thus has been removed from Fig. 1.

Most models identified case studies B and D as the most adaptable, which was consistent with the opinions of the engineers involved in the case studies, with the order of most adaptable to least adaptable being D, B, A, C. Therefore, the models are somewhat accurate in determining the adaptability of several projects in comparison to one another. However, all of the case studies were successfully adaptively reused, despite over half of the models attributing average scores below 60%, suggesting they are less accurate when assessing individual buildings.

4.1 Overall Value of Models

From this analysis, we conclude that the main value of these models lies in their ability to help inform decisions between reusing several buildings, as understanding which is more adaptable helps developers with multiple assets to decide which building to focus on, helping to analyse adaptability at a portfolio level. However, there is less value in using the tools to assess a singular building, as most of the final outputs don't give suggestions as to what to do. While they can still potentially be used to persuade building owners to investigate adaptability, they would need to explain why the building is or is not adaptable to provide more value. As development often occurs on a building-by-building basis, these models may not be very valuable and may further suggest why they aren't being used.

5 Conclusion and Recommendations

This study assessed the approaches used by 9 adaptability assessment models, using four UK-based adaptively reused case studies, drawing conclusions about the models' usability, reliability and overall value, which has not previously been done. There are four main recommendations for future models to address the shortcomings of the current models:

1. Models should be interactive tools. This would allow for filtering, for example, if a particular use type is desired, then this can be selected, which will filter out the more irrelevant questions automatically, making it more applicable to different building types. It would also be able to automatically do post-processing, keeping a database of other adaptively reused buildings, so the user can compare their building to successful projects. There is also the scope to give the user a more in-depth answer, explaining which adaptability strategies are more relevant to that building.
2. Models should be split into several parts. A non-technical section could be used by building owners and non-experts to infer further information about the building, but with more uncertainty; the second part would ask technical questions about the building and be able to provide a more reliable adaptability assessment.
3. If social value is included, and hasn't already been considered during planning, its effect on adaptability should be calculated separately from the physical adaptability. This would mean that if there is a lot of social value in reusing the building, but it cannot safely be reused, then the social value of the reuse assessment will not affect the output for the physical adaptability potential. The social wants are also more likely to be subjective questions, so any bias in answering the questions would also not affect the physical adaptability potential score.
4. Models should provide tangible recommendations to the user, rather than just providing an adaptability score, to make the outputs more valuable to developers with a singular building, rather than just large portfolio holders. This would also give users some direction for their projects and could inspire action. These recommendations could be based on outcomes from adaptive reuse projects, allowing the user to compare their building to real examples, making the outputs more valuable to building practitioners.

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Reuse of Post-Event Waste: A Case Study of Circular Design Involving the Academic Community

Silvia Tedesco(✉), Elena Montacchini, Nicolò Di Prima, and Angela Lacirignola

Department of Architecture and Design, Politecnico di Torino, Turin, Italy
silvia.tedesco@polito.it

Abstract. Temporary events, characterised by their brief timeframes, present considerable challenges in terms of material consumption. Often, the materials used during these events quickly become waste, even though they retain a high residual value that is not exploited for reuse. As a result, these events have a significant impact on the built environment, highlighting the need to rethink cultural, design, and organisational approaches in order to promote systemic change. This article describes a project focused on experimenting with circular design through a specific case study centred on recurring university temporary events organised at the Politecnico di Torino (Italy). This initiative was carried out by a multidisciplinary team of architecture and design students and professors, with the goal of recovering materials from events and making them accessible to the academic community for reuse. The project included an analysis of the actors involved in the process, the quantification of waste, the exploration of opportunities for material recovery, and experimental activities. This research resulted in the development of prototypes and new scenarios for reuse and sharing. The case study provides an opportunity to develop new organisational and management models aimed at extending the useful life of post-event materials, which may be applied in other contexts. Additionally, this initiative offers an educational opportunity to train future professionals through innovative teaching and research-through-design methods, focusing on crucial topics related to the ecological transition and fostering a culture that views waste as a resource.

Keywords: Circular Design · Reuse · Temporary Events · Post-Event Waste · Teaching and Research-Through-Design

1 About Temporary Events and "Cultural Waste": An Introduction

Temporary events, characterised by their brief timeframes, present considerable challenges in terms of material consumption. Often, the materials used during these events quickly become waste, even though they retain a high residual value that is not exploited for reuse [1].

In particular, materials that include graphic elements communicating a coordinated visual identity and event-specific content become obsolete as soon as the event is over.

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As a result, these materials have a significant impact on the built environment [2, 3], highlighting the need to rethink cultural, design, and organisational approaches in order to promote systemic change [4, 5].

This article describes a project focused on experimenting with circular design through a specific case study centred on recurring university temporary events organised at the Politecnico di Torino (Italy) and on the "cultural waste" generated through the production, staging, communication, and use of temporary cultural activities.

This type of waste includes, among others, signage (banners, panels, totems), stage design components, exhibition and stand materials, printed items, and single-use products such as fabric bags, badges, customised lanyards, and accessories. At the end of the event, these materials are typically discarded because they are no longer communicatively relevant, cannot easily be reused, or are not convenient to store and refurbish.

To illustrate the scale of the problem, in 2024 alone the Politecnico di Torino organised 10 large exhibition installations, including 'Salone dell'Orientamento', 'A&T Automation & Testing Fair', 'Biennale Tecnologia', 'Salone Internazionale del Libro di Torino', and the initiative 'PoliTO for Peace', as well as 15 additional exhibition projects supporting promotional initiatives. These temporary and recurring events produced large quantities of roll-ups, coverings, signage, banners, totems, and other communication materials that are typically not reused.

The project described in this article involved a multidisciplinary team of architecture and design students and professors with the goal of recovering materials from events and making them accessible to the academic community for reuse. The project included: a systemic analysis of stakeholders and materials involved in the process; the exploration of opportunities for material recovery; experimental activities aimed at producing prototypes; and the development of new reuse scenarios.

The exploration of this specific case study represents an opportunity not only to propose new organisational and management approaches to extend the useful life of "cultural waste" that would otherwise be sent to landfill, but also, more broadly, to raise awareness and train future professionals on key issues related to the ecological transition.

Although focused on temporary events, the strategies explored are also relevant to broader building-sector practices, particularly in relation to interior fit-outs, exhibition systems, and temporary installations, where short life cycles and material turnover present similar challenges.

2 A University Case Study: Context, Project and Key Actors

For several years, the Politecnico di Torino has been integrating sustainability principles into its activities in teaching, research, third mission initiatives, and campus management, as explicitly stated in its University Strategic Plan, the institutional document defining the long-term vision and objectives of the university [6].

Among the priority action lines is the responsible management of resources within a circular economy perspective. Following the "reduce–reuse–recycle" approach, actions undertaken across the campus include, for example: plastic-free bars and cafeterias; distribution of reusable water bottles to new students and staff; new waste separation

stations; electronic waste (WEEE) collection; responsible procurement policies; initiatives for reusing post-consumption materials generated by the university. Campus sustainability represents the broader framework within which the project described in this article is situated.

The project investigates post-event waste related to the set-up and communication of large events organised by the Politecnico di Torino and open to the public. In particular, the project focuses on two events: i) 'Salone dell'Orientamento', an annual event designed to guide high school students in choosing their university path through informational stands on bachelor's and master's programmes, thematic meetings, open lectures, and laboratory visits; ii) 'Biennale Tecnologia', a biennial cultural event dedicated to exploring the complex relationship between technology and society and addressing the impact of innovation on the environment, democracy, health, and work through lectures, dialogues, debates, exhibitions, and performances hosted in the university's main venues.

These events, which take place regularly, generate recurring waste materials (flags, banners, panels, etc.) whose graphics make them unusable for subsequent editions. The challenge is therefore to identify ways to reuse and manage these post-event materials within the university, extending their useful life.

The project was developed through the collaboration of multiple actors within the academic community of the Politecnico di Torino. Specifically, it emerged from the collaboration between the University Sustainability Division, which promotes sustainable initiatives and practices within the campus, and students and professors from the Master's degree programmes in Architecture and Design, who developed proposals and scenarios within the course Designing and Developing the Circular Economy (academic year 2024/2025) [7].

The project also benefited from the support of the Exhibition Design, Graphics and Merchandising Office, responsible for exhibition design projects and visual identity for university initiatives, and from the LaSTIn Laboratory (Laboratorio Sistemi Tecnologici Innovativi) of the Department of Architecture and Design, which supports teaching and research activities related to technological innovation and sustainability.

3 Post-Event Materials: Analysis, Design, and Experimentation Activities

The project included field research, desk research, design activities, and laboratory experimentation aimed at giving a second life to the "cultural waste" generated by the university.

Following a teaching and research-through-design approach [8], the design and experimental practice carried out by the multidisciplinary team of students and professors served as a means of generating new knowledge. The objective was not limited to producing final artefacts, but rather to identify new potential processes, new actor networks, and new scenarios for the reuse of post-event materials.

The first phase of field research was conducted through interviews with staff from the Exhibition Design, Graphics and Merchandising Office and through on-site observations conducted at the end of Politecnico di Torino events. These activities made it possible to

analyse the organisation of university events, map and represent processes, actors, and materials, and identify inefficiencies and the main types of post-event waste materials.

Event design, organisation, and management are handled by the Exhibition Design Office, which is also responsible for drafting tender specifications and assigning the supply of materials to specialised external companies. According to these specifications, exhibition materials are generally dismantled and disposed of by the suppliers at the end of the event, with landfill as the most common end-of-life destination.

Only a small portion of materials - those considered suitable for experimental recovery projects - is kept and stored within the Politecnico di Torino. However, this practice faces difficulties due to the absence of dedicated storage spaces and the lack of systematic cataloguing, resulting in materials accumulating over time in an uncontrolled way.

Among the most frequently used and quantitatively significant materials in large university events are: 'Piuma' panels, also known as sandwich panels, consisting of a polyester core and two external PVC sheets; Forex panels, a rigid and lightweight plastic material made of expanded or semi-expanded PVC; flag fabric banners, printed on fire-retardant polyester nautical fabric; PVC banners, widely used in exhibitions due to their durability and high print quality (Fig. 1).

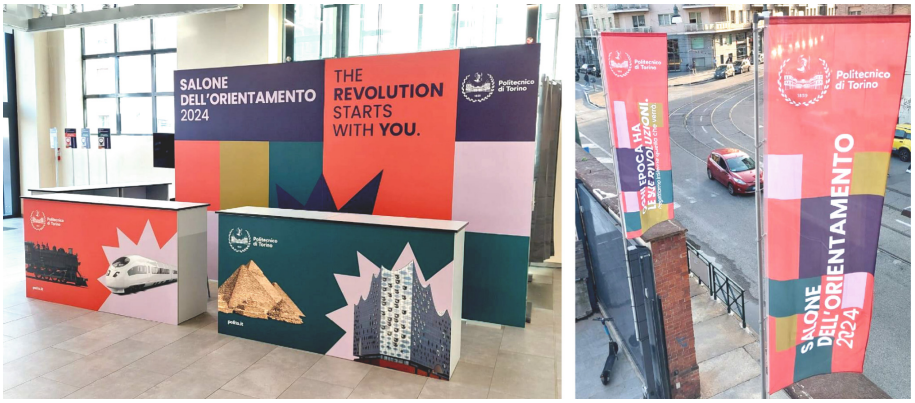


Fig. 1. Example of display materials used for the 2024 "Salone dell'Orientamento" (Careers Fair) at the Politecnico di Torino

These materials present common critical issues: their graphic customisation prevents reuse in subsequent events, and in some cases their multi-polymeric composition makes them difficult to separate and recycle at the end of life.

Although the Exhibition Design Office is working to intervene upstream in the design phase so that exhibition systems can be reused across multiple event cycles, the extreme temporariness of the materials currently used and the absence of consolidated recovery strategies still represent a significant waste of resources.

To identify alternatives to landfill disposal, the field research phase was followed by desk research exploring reuse possibilities through the analysis of international case studies and best practices. These case studies provided references not only for constructive solutions or reuse strategies but also for recovery processes activated through

the involvement of new territorial stakeholders beyond the companies responsible for producing, installing, and dismantling the materials.

In parallel, the available materials were explored through an analysis of their physical and sensory characteristics. The components are highly heterogeneous: rigid materials such as panels and soft materials such as fabrics. Within these categories, materials differ in mechanical resistance, surface treatment, durability, and semantic characteristics. Observation, study, manipulation, and experimentation through cutting, perforating, gluing, and sewing guided the development of design concepts, which were subsequently prototyped at full scale in the laboratory.

The design concepts did not focus exclusively on the development of new objects made from recovered materials but also explored systemic processes and scenarios capable of bringing materials back into circulation. Particular attention was given to identifying new actors to be involved in the process, with a focus on the academic network (students, professors, laboratories, associations, and student teams) and local small enterprises engaged in material transformation.

4 Towards a "Circular" University: Prototypes and Scenarios for the Reuse of Post-Event Materials

Focusing on the academic community - particularly students - made it possible to identify unmet needs related to everyday university life, such as temporary and informal supports for working individually or collaboratively outside classrooms (e.g., portable laptop tables, picnic blankets, desks), as well as the need for low-cost household objects such as lamps, laundry baskets, and storage containers (Fig. 2).

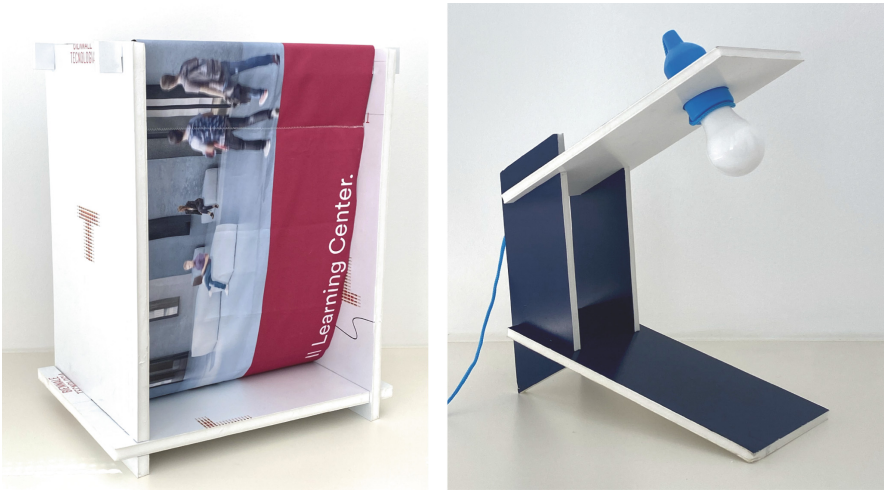


Fig. 2. Examples of prototypes made from post-event waste. On the left, a laundry basket; on the right, a table lamp. Prototypes and pictures by M.E. Cardinale, G. Gaminara, M.G. Romano, S. Rovelli, E. Scarsella, E. Vaira

This led to the development of a catalogue of objects prototyped directly by students with the support of the LaSTIn Laboratory. The prototyping phase allowed the feasibility of design hypotheses to be verified through a material-based approach that prioritised minimising processing steps and optimising the use of available materials. The goal was to avoid generating additional offcuts or waste while ensuring the most efficient possible use of resources and technologies suitable for self-construction and easy replication.

Together with the catalogue of objects, new organisational and management models for reuse were also proposed. Three main reuse modalities were identified.

The first modality involves acquiring post-event materials immediately after the event. Some materials may be booked online before the event and collected during dismantling by student teams for prototyping activities or by professors interested in using the materials in their courses. Individual students may also collect materials and receive assembly instructions to build objects from the catalogue or develop their own projects.

The second modality consists of organising educational and social activities structured as theoretical and practical workshops dedicated to reuse and circularity principles. Participating students produce objects using event materials under the guidance of professors and experienced students. Even simple objects - such as storage containers - can be produced quickly with basic tools, becoming concrete opportunities to learn and experiment with circular design principles in a collaborative environment (Fig. 3).

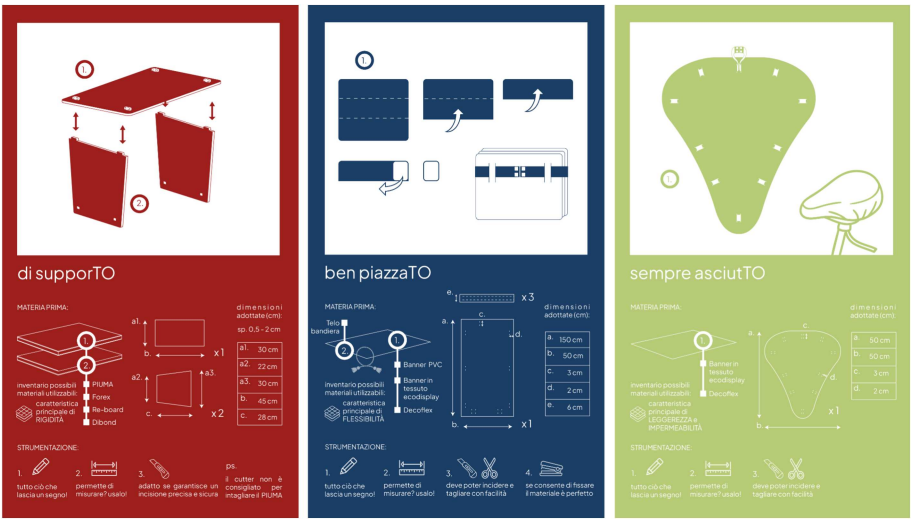


Fig. 3. Examples of assembly instructions for creating objects from post-event waste. Project by A. Cochis, G. Di Lucente, M.V. Nicastro, M. Oberto

The third modality involves the production - supported by the university - of objects useful for everyday campus life, which would then be made available to students through sharing systems. Sharing objects such as portable laptop tables or picnic blankets represents an opportunity to promote a culture of shared use and to move beyond individual

ownership. It also encourages informal moments of study and relaxation, fostering the use of open spaces and social interaction within the academic community.

Prototypes and new organisational and management scenarios were shared with the Exhibition Design, Graphics and Merchandising Office and the Sustainability Division of the Politecnico di Torino. The Sustainability Division will further develop and implement projects beyond the educational context in which they originated by launching several pilot experiments. The first experimentation, related to the reservation of post-event materials, began during the "Salone dell'Orientamento" in March 2026. More than 150 post-event materials - including forex panels, PVC panels, and flag banners - ranging in size from 1000 × 200 cm to 35 × 50 cm, were made available for reservation without usage restrictions. The materials could be reused for teaching activities, design workshops, prototypes and models, as well as personal or social initiatives. Participants were also asked to share photographs documenting the reuse of the reserved materials, which were later published on social media channels. All items were fully booked within a few hours. The success of the initiative, involving professors, students, and laboratories, led to its replication during the "Biennale Tecnologia" event in April 2026.

Additional experiments will be organized by the Sustainability Division as workshops within sustainability-focused festivals, together with the activation of pilot sharing initiatives across different campuses of the Politecnico.

5 Discussion and Conclusion

This project resulted in the development of prototypes and the definition of new scenarios for the reuse and sharing of so-called "cultural waste". The outcomes were presented to the Exhibition Design, Graphics and Merchandising Office and the Sustainability Division of the Politecnico di Torino, initiating a constructive institutional dialogue on the management of post-event materials and their potential reintegration into the university system.

Originating within an educational context, the project is intended to be further implemented and assessed at the institutional level, evolving from a teaching experiment into an operational strategy embedded in university practice. Preliminary results suggest promising impacts in terms of materials diverted from landfill and high participation levels; future developments will include more systematic monitoring of quantities, user engagement, and organisational uptake to assess long-term circularity performance.

The project shows how academic experimentation can contribute to shaping scalable and transferable approaches, potentially adaptable to other cultural contexts. While rooted in a specific institutional context, the proposed scenarios highlight a set of replicable elements - such as stakeholder collaboration, material mapping, and low-threshold access to reuse - that can be adapted to other universities and building-sector practices, where short life cycles and material turnover present similar challenges. Nevertheless, operational aspects (e.g. storage availability and internal governance) remain context-dependent.

From an educational perspective, the initiative supported the training of future professionals through research-through-design methodologies and interdisciplinary learning processes. By engaging with real-world constraints and opportunities related to the ecological transition, students are encouraged to adopt a systemic perspective that reframes

waste as a resource within circular design paradigms. More broadly, the project generates social impacts that extend beyond the students directly involved. By activating concrete practices of reuse and sharing within the university campus, it fosters a cultural shift across the academic community. Sustainability is thus approached not as an abstract principle but as an operational and situated practice rooted in everyday contexts and capable of influencing collective behaviours and ways of thinking.

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Living Wall Systems As Educational, Cultural and Climate-Adaptation Devices: A Case Study

Carlotta Fasano(✉)

Department of Architecture and Design, Politecnico di Torino, Turin, Italy
carlotta.fasano@polito.it

Abstract. Climate change increasingly affects liveability and thermal comfort in dense urban areas, requiring cities to adopt adaptive and user-centered strategies. In this context, Nature-Based Solutions (NBS) represent efficient tools in urban regeneration and social cohesion. Turin is advancing this approach through its Climate Resilience Plan and Green Infrastructure Strategic Plan, promoting initiatives such as rooftop gardens on the Lidl supermarket in Via Bologna and the NBS Living Labs implemented within the EU project ProGIreg.

This contribution examines the Living Wall System (LWS) installed in 2025 in the courtyard of the Pertini School in Turin. Initially designed as a temporary installation for the ATP Finals, the system was repurposed as a permanent green infrastructure. The study investigates how the LWS evolved from a simple regeneration measure into an educational and cultural device that makes climate adaptation principles tangible, fostering environmental awareness and inclusive participation.

The methodology combines a qualitative assessment of spatial, cultural and pedagogical dimensions with a quantitative framework based on consolidated scientific data on LWS performance. Literature-based indicators provide a benchmark for understanding the system's potential for urban heat-island mitigation and air-quality improvement, while field-based qualitative analysis highlights the architectural and pedagogical value of the installation, which enables students to directly observe system functioning and translate environmental benefits into accessible learning experiences.

Results confirm the capacity of LWS to integrate environmental, social and educational benefits within school contexts. However, high installation and maintenance costs remain a barrier, underscoring the need for more scalable, affordable and circular solutions.

Keywords: Nature-Based Solutions (NBS) · Living Wall Systems (LWS) · Climate Adaptation · Environmental Education · Urban Regeneration

1 Introduction

Climate change is increasingly affecting urban liveability, thermal comfort and public health, particularly in densely populated areas where built surfaces intensify heat accumulation and limit ecological regulation processes. According to the Intergovernmental

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Panel on Climate Change (IPCC), cities are both major contributors to climate change and highly vulnerable systems exposed to rising temperatures, extreme weather events and deteriorating air quality [1]. Consequently, climate adaptation has become a central objective of urban policy and design, requiring strategies that integrate environmental, social and infrastructural dimensions.

Within this framework, Nature-Based Solutions (NBS) are increasingly recognized as effective and multifunctional instruments to enhance climate resilience while producing co-benefits for biodiversity, health and social cohesion [2]. However, recent studies highlight that many NBS initiatives remain confined to pilot interventions, often lacking scalability, long-term monitoring or integration within circular economy models [3].

Among NBS, Living Wall Systems (LWS) represent a promising vertical greening strategy able to face multiple urban challenges simultaneously. Several studies demonstrate their contribution to surface temperature reduction, mitigation of the urban heath island effect, particulate matter retention and carbon sequestration [4–7]. In addition to environmental benefits, vertical greenery systems are associated with psychological well-being, improved spatial perception and enhanced learning conditions in educational environments [8, 9]. Nevertheless, large-scale implementation remains limited due to installation and governance costs [10]. Furthermore, the socio-pedagogical function of such systems as so far been marginally investigated.

This contribution therefore aims to explore the potential of LWS not only as environmental solutions but also as cultural and educational devices. In this context, the paper analyses the LWS installed in 2025 in the courtyard of the Pertini Comprehensive Institute in Turin as an example of circular recontextualization, where an event-based green installation is transformed into long-term public intervention.

2 NBS in Turin: From Strategy to Practice

The transition toward climate-resilient and circular urban systems requires policies capable of integrating environmental, social and infrastructural dimensions across scales [11]. In this regard, the City of Turin represents a relevant case of institutional alignment between climate adaptation strategies and green infrastructure planning.

Turin's current adaptation trajectory is shaped by two complementary instruments. The Climate Resilience Plan of the City of Turin [12] identifies urban heat island mitigation, soil de-paving and green infrastructure expansion as priority actions to address rising temperatures and climate-related risks. Complementarily, the Green Infrastructure Strategic Plan [13] frames urban greenery as a multifunctional system providing ecosystem services across environmental, social and economic spheres. It explicitly connects green infrastructure to climate mitigation, stormwater management, biodiversity enhancement and public well-being, and recognises the role of public–private partnerships and community engagement as enabling factors for scaling NBS.

Together, these instruments mark shift from fragmented greening interventions toward an integrated urban agenda that includes NBS within planning tools, regulatory processes and long-term development visions.

In addition to policy framing, local experimentation demonstrates progressive NBS implementation. Rooftop gardens realized on a commercial building in Via Bologna

demonstrate how private actors can contribute to ecosystem service provision into dense urban contexts. Similarly, the ProGIreg living lab in Turin [14], developed within the EU Horizon 2020 framework, has provided a structured environment for testing and co-designing NBS in post-industrial neighbourhoods, fostering collaboration among academia, public authorities, private stakeholders and citizens. Within this project an indoor green wall was implemented in schools to improve environmental quality and activate environmental educational pathways [15, 16].

Despite this supportive governance framework, challenges remain in translating strategic objectives into adaptable and resource-efficient interventions able to ensure long-term usability and effective integration into everyday urban spaces. The Pertini case study can therefore be interpreted as a bridging action, connecting policy objectives, circular reuse practices and pedagogical innovation within a single infrastructural intervention, where recontextualization extends the system's life and expand its function within an educational setting.

3 The Pertini Living Wall System

Installed in June 2025 in the courtyard of the Sandro Pertini Comprehensive Institute in Turin, the LWS was originally conceived as a temporary installation for the ATP Tennis Finals and later donated by the Japanese company Nitto to the City of Turin as a permanent green legacy of the event. The municipal administration accepted the donation within the framework of its climate-adaptation strategy and identified the Pertini school courtyard as a suitable site for relocation. The school lies near the Inalpi Arena, the venue of the tournament, and it is characterised by extensive asphalt paving and a blind façade. The relocation was also facilitated by the city's previous experience with the green wall implemented in schools during the ProGIreg project [15, 16].

The system is a 15 × 8m substrate-based modular LWS (VP Modulo®, Verde Profilo [17]) composed of independent expanded polypropylene tray containing growing medium and integrated irrigation components. Approximately 300 modular trays were installed, hosting about 950 plants including Fatsia japonica, Lonicera nitida, Hedera helix and Liriope muscari. The modules are installed on a lightweight aluminium supporting frame anchored to the existing façade, minimising structural load while ensuring durability and adaptability. The irrigation system is automated and designed to optimise water consumption (see Fig. 1).

A key technical feature of the system is its design for disassembly, allowing modules to be independently removed and replaced. This modularity enabled the dismantling of the installation from the event site and its reassembly in the school courtyard without structural reconfiguration, according to circular construction principles [18].

In line with established evidence on substrate-based LWS, this system can be framed within consolidated environmental performances ranges. Tabatabaei & Fayaz' (2023) studies report air temperature reductions of up to 3 °C in proximity to vegetated façades under specific climatic conditions, contributing to urban heat island mitigation [5]. CO_2 sequestration values between 0.44 and 3.18 kg CO_2eq/m^2/year have been documented depending on plant species and system configuration [7], while airborne particulate matter retention has been observed in comparable living wall typologies, contributing to improved urban air quality [6].



Fig. 1. Living Wall System installed in the Pertini School courtyard.

Although no direct environmental measurements were conducted in this study, the technical configuration of the Pertini installation aligns with those analyzed in the literature, suggesting that the LWS may contribute to local micro-climatic mitigation and environmental regulation in its immediate urban context. This assumption provides the basis for identifying a limited set of indicators that could be monitored in future phases, including surface-temperature variations between different surfaces, seasonal plant survival rate, irrigation demand, maintenance frequency and visible particulate deposition on leaf surfaces.

4 A Multilevel Approach

This research adopts a multilevel approach integrating quantitative aspects based on literature benchmarks with qualitative cultural and pedagogical analysis in order to provide a multidimensional interpretation of the Pertini LWS, in line with integrated NBS evaluation models [19].

The quantitative component relies on literature-reported performance indicators related to substrate-based LWS relevant to climate adaptation, including surface and air temperature mitigation, air quality improvement and carbon sequestration. These parameters serve as comparative references rather than site-specific measurements, positioning the Pertini installation within established environmental performance ranges and defining a scientifically grounded reference framework to be integrated into the educational design of the project.

A participatory educational programme was incorporated as both a dissemination tool and a qualitative research instrument. The activities, developed in collaboration with teachers, involved second-year middle school students and classroom-based sessions with courtyard hands-on activities in order to connect theoretical knowledge with direct observation.

Classroom-based discussions introduced climate change impacts, urban heat islands effect, evapotranspiration processes and air-quality dynamics. Literature-derived quantitative benchmarks were simplified and presented as scientific support to explain what LWS are, how different typologies operate and what environmental contribution they may provide.

Subsequently, courtyard hands-on exercises allowed students to test and critically reflect on the theoretical principles previously discussed. These activities were conceived as guided experiential sessions supporting the qualitative evaluation of the LWS as a cultural and pedagogical device.

In parallel the research also included an assessment of circular and spatial valorisation dimensions considering the system's design for disassembly, relocation and reuse, as well as its architectural impact on a previously neutral courtyard façade. This reflection contributes to understanding how material reuse and spatial enhancement reinforce the cultural potential of the system.

5 Pedagogical and Socio-Cultural Outcomes of the Pertini LWS

While temporary event-based installations are typically conceived for short life cycles and frequently dismantled after the event, the relocation of Pertini LWS extended its life beyond the sporting event and ensured functional continuity within a public educational setting. In this sense, circularity operates simultaneously at material, functional and spatial levels: the components were reused and their purpose evolved from temporary representational installation to long-term climate-adaptive educational device. Along with the material reuse, the intervention introduced a green landmark in the school courtyard strengthening the place identity. According to studies enhancing the positive effects of vertical greenery systems on perceived environmental quality and people well-being in built contexts [8], the Pertini LWS operates as a regenerative architectural tool, reconfiguring the school courtyard perception and increasing its attractiveness. This spatial requalification reinforces the socio-cultural dimension of the intervention, extending its impact not limited to environmental regulation alone.

Moreover, the developed educational programme allowed the enhancement of the LWS as a pedagogical device. Introductory classroom-based sessions functioned as interactive and participatory learning environments (see Fig. 2a). Simplified scientific data were shown through images, videos and guided questions, actively engaging students in the discussion. Examples of similar NBS implemented within the local urban context were presented to emphasise the tangible nature of these solutions. Students frequently recognised such installations, demonstrating the activation of curiosity and contextual awareness.

Field-based activities in the courtyard further consolidated this learning process. The opportunity to physically observe and analyze the wall's structure and components enabled true understanding of LWS's technological functioning. Subsequently, students measured surface temperatures of asphalt, the bare façade and the vegetated wall using a thermal camera, allowing discussion on solar radiation absorption, material albedo and cooling mechanisms. Air-quality awareness was supported through leaf-surface cleaning tests providing visible evidence of particulate deposition (see Fig. 2b). Finally,

plant inventory documentation allowed students to estimate potential CO_2 sequestration using online available carbon calculation tools [20], linking biomass presence to climate mitigation processes.

These activities enabled students to translate theoretical data into observable phenomena, experiencing the LWS as an interface through which climate-adaptation principles become tangible. Technical learning emerged from students' ability to relate the system's material and technological components to its environmental functions. In addition, a post-activity questionnaire was administered by the teacher to assess students' perceived learning, interest and awareness of NBS and urban sustainability, representing a first step toward a more structured evaluation of the initiative's educational and social impact.



Fig. 2. **a.** Classroom-based concept introduction. **b.** Hands-on "leaf-cleaning" test

Overall, the contribution recognizes the Pertini LWS qualitative potential that extends beyond the energy and environmental performance commonly addressed in literature. By integrating circular reuse, spatial requalification and structured educational engagement, the system operates as an environmental, pedagogical and socio-cultural device, reinforcing its relevance within contemporary climate-adaptation strategies.

6 Conclusions

The Pertini case study contributes to current debates on the sustainable and circular transformation of the built environment by demonstrating how LWS can operate simultaneously as climate-adaptation strategy, circular reuse intervention and educational device. While environmental performance of LWS has been extensively analysed in literature, this example highlights their potential as cultural and pedagogical tools.

The relocation of a temporary installation into a permanent school setting exemplifies a form of circular recontextualization, where material reuse, functional transformation and spatial regeneration converge, extending material lifespan and generating social value. Moreover, through structured pedagogical integration, the LWS becomes a tangible interface through which students engage with climate-adaptation principles, reinforcing environmental literacy and collective awareness.

However, installation costs, technical complexity and maintenance requirements remain critical constraints for wider diffusion, particularly in resource-limited contexts. The present study is also limited by the absence of long-term site-specific environmental monitoring, while the post-activity questionnaire already administered provides a basis for further assessing the educational and social impact of the initiative. Future research should therefore focus on scalable and economically sustainable models, supported by simple monitoring protocols that combine environmental indicators, maintenance data and educational and social-awareness assessment. This would allow future developments to integrate environmental performance, circular principles and pedagogical value within a more evidence-based framework.

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How Well Do Circularity Indicators Describe Recovery Potential in Existing Buildings at the End of Life? A Case Study in Belgrade, Serbia

Milica Nikolić[1], Aleksandra Parezanović[1(✉)], Zorana Petojević[1,2], and Ana Nadaždi[1]

[1] Faculty of Civil Engineering, University of Belgrade, Belgrade, Serbia
aparezanovic@grf.bg.ac.rs

[2] School of Architecture, Design and Civil Engineering, Zurich University of Applied Sciences, Winterthur, Switzerland

Abstract. Achieving a circular built environment requires reliable methods for assessing existing buildings as material banks at the end-of-life, yet most circularity indicators are developed primarily for the early design phase. Even those indicators intended for end-of-life assessments remain insufficiently validated. This study examines how different circularity indicators describe the same existing building when applied under identical data constraints and system boundaries, enabling a controlled comparison of scenario-based end-of-life circularity assessments. Three frequently cited end-of-life indicators were applied to a 1930s residential building in Belgrade, Serbia, using a single and consistent material inventory derived from archival documentation and BIM-based quantification. The results show relatively high agreement between the compared MCI-based approaches at the material level, but substantial differences at the element, system, and building levels. This confirms that circularity indicators are not interchangeable and that their interpretation depends strongly on the assessment level, data availability, and methodological assumptions. While such assessments may be feasible for individual existing buildings to some extent, their application to neighborhood-scale studies remains limited without simplified input requirements and standardized calculation procedures.

Keywords: Building Circularity Indicator · Circularity Assessment · Material Circularity Indicator · Pre-Demolition Audit · Resource Recovery · Reuse Potential

1 Introduction

Since over 93% of virgin materials continue to enter the global economy [1], the need for comprehensive models capable of tracing material flows and identifying realistic recovery potential has become increasingly vital. The existing building stock, much of it aging [2, 3] and approaching unavoidable renovation or demolition, represents a

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substantial yet unexplored reservoir of secondary materials that may be reintroduced into circular resource cycles at the end of their service life.

In response, a wide range of circularity indicators (CIs) has been proposed. A systematic literature review was conducted following PRISMA guidelines, searching Scopus, Web of Science, and ScienceDirect for peer-reviewed research published between 2010 and 2025. The search combined Boolean operators and terms such as ("circularity indicator" OR "circularity metric" OR "circularity index") AND ("construction industry" OR "built environment" OR "building"). Studies were included if they defined or applied a CI in the built environment; grey literature and unrelated sources were excluded. From over 880 screened records, a final set encompassing nearly 100 indicators was identified.

The identified indicators are primarily developed for the design phase [4–6], where input data are usually available and accurate. In contrast, only 11 construction-specific indicators address the end-of-life (EoL) phase. All are quantitative and vary considerably in their level of assessment, spanning material, element, and whole-building scales—a breadth that nonetheless reveals the absence of a standardized approach to assessing circularity at the EoL phase.

Finally, CIs are rarely tested and validated on real-life (existing) building case studies; only a small number of studies have been conducted [4, 6, 7], limiting their empirical robustness and practical reliability. This situation is further complicated by the fact that buildings constructed before the mid-twentieth century rarely have complete documentation; archival drawings are often fragmentary, material specifications are unavailable, and details of layers and joints are frequently unknown. Within the analyzed literature, no case studies were identified that focus on existing buildings built before the mid-twentieth century, despite their significance in the European urban landscape. These limitations raise a fundamental research question: How can circularity be assessed for existing buildings under real-world conditions when essential data are incomplete or absent?

The present research directly addresses this issue by examining how applicable and feasible CI assessments are for existing buildings at the EoL phase under incomplete documentation and data constraints. The most frequently cited indicators were applied to the same building using identical system boundaries and data limitations, ensuring a controlled and comparable scenario-based assessment. This comparison is particularly important for understanding the extent to which different indicators describe the circularity of the same building and how useful such results are for decision-makers in the end-of-life phase. Given the growing interest in applying circularity assessments beyond individual buildings, it is also essential to understand how feasible and meaningful such calculations would be at the neighborhood or higher scales. It further reflects on how sensitive each indicator is to the assumptions required when documentation is incomplete. Finally, it contributes to the knowledge base by providing an additional case study.

2 Methodology

2.1 General Approach

The methodology adopted in this study is structured to ensure a transparent, consistent, and replicable circularity assessment of existing buildings at the EoL phase. It consists of six steps, which are illustrated in Fig. 1: 1) creating a database of circularity indicators, 2) filtering the database to identify relevant EoL phase indicators, 3) ranking the indicators and selecting three most frequently cited, 4) adapting and calibrating the selected indicators for application to the case study, 5) acquiring all available data for the case study (including digital model generation), 6) calculating indicators and interpreting results.

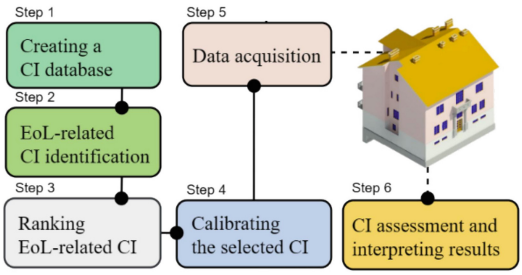


Fig. 1. EoL building circularity assessments' methodological steps

The workflow began with the creation of the CI database, and the identification of 11 EoL indicators. Using MAXQDA 24[1]'s automatic coding function, each indicator was searched in the literature using multiple name variants, full names, abbreviations, and alternate forms. This ensured that each occurrence of every indicator in the texts was recorded. The results of the automatic coding were then manually verified to eliminate duplicates and inaccurate occurrences. Based on the validated data, the indicators were ranked by frequency of occurrence.

For the case study application, the three indicators that appeared most frequently in the analyzed literature were selected: Material Circularity Indicator (MCI), Building Circularity Indicator (BCI), and Whole-Building Circularity Indicator (WBCI).

Given that this study aims to assess circularity at the building level, the BCI and WBCI were applied in accordance with their original formulations, as proposed by Verberne [5] and Khadim et al. [4]. Both indicators follow a hierarchical calculation that progresses from the material level to the element level, then to the system level, and finally to the building level. In contrast, MCI is originally defined only at the material level, which requires adapting it for building-level assessment to ensure comparability across all indicators. In the adapted approach, MCI was first calculated by material [8]; the resulting values were then weighted by material mass, and the overall building-level circularity was obtained by dividing the sum of the weighted values by the total mass of all materials.

[1] MAXQDA - MAXQDA is a software tool for qualitative and mixed-methods data analysis, enabling systematic coding, searching, and organization of textual, visual, and multimedia research materials available at https://www.maxqda.com/.

2.2 Data Acquisition

An existing residential building situated in the Palilula municipality of Belgrade, Serbia, was selected as the case study. The building was constructed in 1932 and has a configuration of basement, ground floor, first floor, and attic (B + GF + 1 + A). According to the National typology of residential buildings in Serbia [9], it is classified as archetype B5, e.g., a multi-family house (MFH) built in a row in the period between 1919 and 1945. This archetype represents the most common multi-family residential building type within the dominant construction period identified in the selected study area of Palilula municipality, which is being analyzed as part of the Circ-Boost project funded by the Horizon Europe programme (Grant Agreement No. 101082068).

As the case study building was constructed in 1932, data collection was limited to the available archival documentation from the Historical Archives of Belgrade. The documentation included floor plans, sections, elevations, and a brief technical description covering the structural system, principal materials, floor and roof constructions, and wall finishes. It did not contain information on floor and ceiling finishes, joint details, and exact material specifications. This information had to be assumed using typology-based material assemblies and descriptions for the B5 MFH archetype.

To support material quantification needed for indicator assessment, a digital model of the building (BIM model) was developed and used to generate an inventory of building materials and elements (material take-offs). The model included the main structural and architectural elements, while furniture, equipment, and service systems were outside the scope of the assessment. Material quantities were extracted from the model, while material masses were calculated by multiplying the corresponding volumes by material density values. The resulting material inventory provided the common input dataset for the calculation of the selected circularity indicators.

The assumptions used in the circularity assessment cover a wide range of parameters, including material physical and chemical characteristics, feedstock composition, waste fractions, recovery efficiencies, service life, end-of-life pathways, and maintenance or construction phase losses. Their reliability ranges from high, where data come from standards or other formal sources, to low, supported mainly by grey literature, industry practice, or expert judgement.

3 Results and Discussion

3.1 CI Assessment at the Material and Element Level

Figure 2 presents the comparative results at material and element levels using a dual heatmap: a green-yellow-red scale for material-level performance (MCI-E, MCI-V, MCI-K) and a blue-red scale for element-level performance (MCI-E′, PCI-V, ECI-K). For acronym definitions, see the note accompanying Fig. 2.

At the material level, a high degree of convergence is observed among different methodologies, particularly for mineral-based materials. The convergence for mineral-based materials is expected, as all three formulations yield identical results when construction losses, maintenance flows, and bio-based fractions are negligible. The results show full alignment of MCI-E, MCI-V, and MCI-K for foundation materials and for

	*	Element	Material	MCI-E	MCI-V	MCI-K	MCI-E'	PCI-V	ECI-K
Foundation	ST	Foundation	rein. concrete	0.40	0.40	0.40	0.4	0.4	0.4
	ST	Slab-on-grade (asphalt)	gravel	0.40	0.40	0.40	0.48	0.22	0.48
	ST		concrete	0.40	0.40	0.40			
	SP		cem. screed	0.94	0.94	0.94			
	SP		asphalt	0.85	0.85	0.85			
	ST	Slab-on-grade (terazzo)	gravel	0.40	0.40	0.40	0.47	0.2	0.47
	ST		concrete	0.40	0.40	0.40			
	SP		cem. screed	0.94	0.94	0.94			
	SP		terazzo	0.85	0.85	0.85			
Exterior	SP	Ext. wall 1	lime-sand pl.	0.93	0.93	0.88	0.71	0.25	0.71
	ST		clay brick	0.70	0.70	0.70			
	SK		silicate f. pl.	0.70	0.70	0.70			
	ST	Ext. wall 2	clay brick	0.92	0.93	0.92	0.89	0.27	0.89
	SK		silicate f. pl.	0.70	0.70	0.70			
	SP	Ext. wall 3	lime-sand pl.	0.93	0.93	0.88	0.71	0.25	0.71
	ST		clay brick	0.70	0.70	0.70			
	SK		silicate f. pl.	0.70	0.70	0.70			
	SK	Windows	wood	0.85	0.70	0.70	0.85	0.71	0.74
	SK		glass	0.85	0.85	0.75			
	SK	Ext. doors	wood	0.78	0.55	0.55	0.83	0.64	0.72
	SK		glass	0.85	0.85	0.75			
	SK	Roof covering	gyps. board	0.70	0.70	0.70	0.80	0.43	0.73
	SK		stone wool	0.70	0.70	0.70			
	SK		wood	0.85	0.85	0.75			
	SK		clay roof tile	0.85	0.85	0.75			
	ST	Roof str.	wood	0.55	0.10	0.25	0.55	0.1	0.25
	ST	Ext. stairs	stone	0.85	0.85	0.85	0.85	0.85	0.85
Interior	SP	Int. wall 1	lime-sand pl.	0.93	0.93	0.88	0.72	0.27	0.71
	ST		clay brick	0.70	0.70	0.70			
	SP	Part. wall 1	lime-sand pl.	0.93	0.93	0.88	0.92	0.3	0.91
	SP		clay brick	0.92	0.93	0.92			
	SP	Int. wall 2	cem. sand pl.	0.97	0.97	0.95	0.94	0.24	0.93
	ST		clay brick	0.92	0.93	0.92			
	SP	Part. wall 2	wood	0.93	0.85	0.85	0.93	0.85	0.85
	SP	Int. Doors	wood	0.78	0.55	0.55	0.78	0.55	0.55
	ST	Slabs	rein. concrete	0.70	0.70	0.69	0.70	0.7	0.69
	ST	Attic slabs	wood	0.55	0.55	0.55	0.55	0.55	0.55

*Shearing layers: ST-structure; SP-space plan; SK-skin; Note: MCI-E = MCI based on the Ellen MacArthur methodology; MCI-V = MCI based on the BCI methodology (Verberne, 2016); MCI-K = MCI based on the WBCI methodology (Khadim et al., 2023); MCI-E' - mass- aggregated MCI-E on element level; PCI-V = PCI based on the BCI methodology (Verberne, 2016); ECI-K = ECI based on the WBCI methodology (Khadim et al., 2023);

Fig. 2. Material-level and element-level results

clay brick and concrete across most exterior and interior elements, while the largest discrepancies appear in timber components of the exterior envelope. The wooden roof structure is the most pronounced outlier, with MCI-V scoring 0.10 compared to 0.55 under MCI-E, and notable differences also occur for external wooden doors and window frames. Divergences in timber components reflect two methodological differences: MCI-E credits wood as a bio-based material from Sustained Production, while MCI-V treats it as virgin input; MCI-K additionally penalizes timber through construction and maintenance waste flows in M′, yielding intermediate values. Smaller variations are observed for glass and roof coverings, whereas interior elements remain largely consistent except for wooden internal doors, which again follow the pattern of higher MCI-E values relative to the other two indicators.

A comparative analysis of the element-level results across the three methodologies reveals significant discrepancies, with PCI-V consistently producing the most conservative results in nearly all elements. This is attributable to the disassembly-related factors in Verberne's approach, which penalize elements based on connection types and accessibility at the element level—aspects not accounted for in MCI-E and incorporated in WBCI only at higher aggregation levels. The largest differences occur in roof covering, roof structure, and both external and internal walls, where PCI-V falls 0.37 and 0.70 below the corresponding MCI-E′ and ECI-K results. Ultimately, the lowest PCI-V performances are recorded for slabs-on-grade, external walls, internal walls, and the roof structure.

3.2 CI Assessment at the System and Building Level

The results of the comparative CI assessment at the system and building levels are illustrated in Fig. 3. The system- and building-level comparison shows that discrepancies between methodologies intensify as the scale of assessment becomes more aggregated. At the system level, the data is categorized by shearing layers (structure, skin, and space plan). The skin layer exhibits the largest deviation (0.66 between MCI-E″ and SCI(p)-V), followed by the space-plan layer (0.50 spread between MCI-E″ and SCI-K), while the structure layer remains comparatively stable with only 0.15 variance (between MCI-E″ and SCI-K). At the building level, results show a sharp decline from the theoretical BCI(t)-V of 0.82 to a final WBCI-K of 0.23. This consistent downward trend (0.82 → 0.66 → 0.34 → 0.23) highlights a major discrepancy between different methodologies.

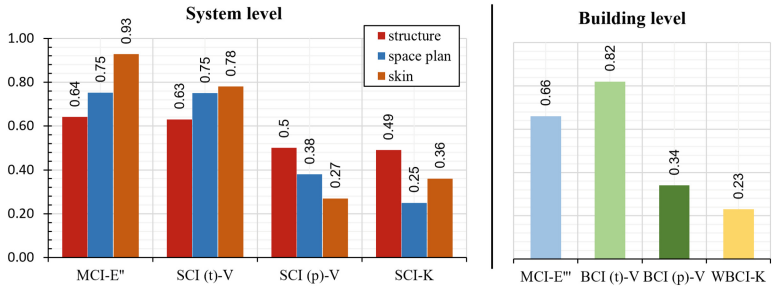


Fig. 3. System-level and building-level results

3.3 Discussion

The results show that the three circularity indicators cannot be used interchangeably, even when applied to the same building with identical boundaries and data. Each operates at a different assessment level and therefore captures different dimensions of recovery potential: material-level indicators identify which materials can be recovered based on physical properties, whereas element-level indicators—by incorporating DfD principles,

connection types, and accessibility—are better suited for guiding selective dismantling decisions. Building-level indicators, in turn, support broader comparisons and prioritization. For EoL decision-makers, this means that the choice of indicator directly shapes the type of information and may lead to different interpretations of a building's circularity performance.

The indicators are not equally sensitive to assumptions and system boundaries adopted in the assessment. Since assumptions are based on inputs with different levels of reliability, their effect on the result is not uniform across indicators. While the different methodologies produced relatively similar results at the material level, larger differences emerged at the element, system, and building levels, where the impact of sensitive assumptions was compounded by inherent differences in mathematical formulation, aggregation logic, and normalization factors.

Although the calculation of EoL CIs is not necessarily complex, it is challenging to apply it to existing buildings when documentation is incomplete, because the assessment requires extensive data preparation and a considerable number of assumptions. This makes transparent reporting of assumptions essential, as different assumptions may lead to different circularity values and, consequently, different EoL decisions. These constraints also question the feasibility of scaling such assessments to the neighborhood or higher level. In this study, even one building required a detailed inventory and multiple assumptions, suggesting that data-intensive methodologies such as MCI are not yet feasible for neighborhood- or city-scale application without substantial simplification.

Finally, the study has several limitations. It is based on a single case study, relies on incomplete historical documentation, and compares indicators developed from different conceptual perspectives and levels of application. Further research should therefore include additional existing building case studies, sensitivity analyses of key assumptions, and methodological simplification for application at larger scales.

4 Conclusion

This study compared three frequently cited CI under identical system boundaries and data constraints to examine how well they describe recovery potential in an existing residential building at the EoL stage. The results show that, although the compared approaches produce relatively similar values at the material level, substantial differences emerge at the element, system, and building levels. Because many key parameters must be assumed rather than measured, the choice of indicator directly shapes the outcome. This confirms that the selected indicators are not interchangeable, as they reflect different methodological logic, aggregation procedures, and sensitivities to assumptions.

From a practical standpoint, the study demonstrates that applying circularity indicators to existing buildings requires extensive data preparation and transparent reporting of assumptions. Even for a single building, the assessment is resource-intensive, raising doubts about the feasibility of scaling such methods to neighborhoods or larger territories without substantial simplification and standardization.

Overall, the findings highlight the need for greater methodological alignment, clearer guidance on assumptions, and more robust data frameworks before circularity indicators can reliably support end-of-life decision-making for existing buildings.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Repeated Assembly-Reassembly Behaviour of Dry Mechanical Joints in Digitally Fabricated Timber Structures

Mahmood Ali and Dan V. Bompa(✉)

University of Surrey, Guildford GU2 7XH, UK
d.bompa@surrey.ac.uk

Abstract. This study investigates the disassembly capability and reusability of dry mechanical connections (DMCs) in digitally fabricated timber structures, using a modular timber arch as a case study. Material characterisation was undertaken in tension, compression, and shear, supported by digital image correlation to establish reference properties and failure modes. At connection level, focused cyclic pull-out tests were conducted to quantify friction-based resistance, wear, and degradation under repeated assembly-disassembly actions. Resistance degradation envelopes were obtained for up to 1000 cycles, indicating gradual reduction of mechanical properties with increase in cycles. A modular arch was manufactured, assembled and tested under mechanical loading. Failure was governed by slip at the mortise-and-tenon connections, indicating that the properties of the DMCs are critical for this structural typology. Consequently, characterisation of cyclic pull-out behaviour at connection level is instrumental to evaluate the suitability of repeated assembly-reassembly of such structures. The study provides experimental evidence directly relevant to circular construction and modular design in the wider context of Performance Based Circular Structural Engineering framework.

Keywords: Design for disassembly · Dry mechanical connections · Cyclic assembly-reassembly · Structural reuse · Modular timber · Circular construction

1 Introduction

A circular solution is to adopt engineered timber systems that can be repeatedly assembled and disassembled (reused) without significant loss of mechanical performance to transform modern practices and aid the transition toward sustainable, circular built environments. Dry Mechanical Connections (DMCs) advance this objective by avoiding adhesives and fasteners through a system of interlocking designs and friction-based load transfer, enabling reversibility and element recovery [1, 2]. Digitally manufacturing integrates timber-to-timber DMCs back into modern, repeatable construction workflows. Computer Numerical Control (CNC) machining (3D subtractive manufacturing) produces planar joint geometries and allows interlocking geometries to be milled with controlled tolerances, supporting modular reuse without adhesives. This application has supported physical projects such as the WikiHouse and The Music Pavilion in Huis

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ter Heide. The DMCs used are derived from traditional Japanese, Chinese, and European timber construction practices, including mortise and tenon (MT), Nuki, scarf, lap, pinned, and notched joints [3]. The connections rely on precise geometric interlock and friction to transfer loads into the foundations, and, with the advancements in digital fabrication, DMC's offer scalable, demountable, and modular design assemblies.

Circularity is a systemic approach that aims to minimise waste and retain the highest utility for as long as possible, expressed through design-for-disassembly that prioritises durability and allows multiple design lives [4]. Recent work on circular structural timber focuses on assessing and grading reclaimed members, highlighting the need to adapt existing grading methods if reused timber is to be treated as a reliable structural resource [5]. The field is shifting from circularity to a predominantly environmental or process-led discussion towards circularity as a problem of structural qualification and future performance, in the wider context of Performance Based Circular Structural Engineering (PBCSE). In the context of DMCs, circularity depends on the material's reclaimability and the structural system's demountability, without causing irreversible damage or significant loss of mechanical performance through repurposing/reusing structural elements in future lives. DMCs' reusability is governed by the stability of friction-based resistance and tolerance-sensitive contact conditions, which degrade over time due to wear, local crushing, and repeated assembly. Quantifying this degradation is essential to turn design-for-disassembly into a measurable reuse metric that can inform new life scenarios [6]. MT joints' cyclic pull-out resistance degradation is proposed and evaluated as key reuse control here.

2 Methodology

2.1 Material Properties

The engineered timber selected was Brazilian Pine Structural Plywood (BPSP), manufactured from Pinus elliottii (Slash Pine) sourced from plantation concessions in Paraná and Santa Catarina, Brazil, and fabricated in sheets measuring 2440 mm × 1220 mm × 18 mm (width × height × thickness). The plywood plates consist of seven veneer layers bonded in alternating grain directions using phenol-formaldehyde adhesive, conforming to BS EN 636:2012, with mechanical properties characterised per BS EN 789:2004. The homogeneous cross-laminated structure provides dimensional stability. Tests included tension (dog-bone), compression, shear, and cyclic MT joint loading, to evaluate stiffness, strength, and assembly-disassembly capabilities. The material tests aim to establish mechanical strength properties, evaluate the effectiveness of the interlocking MT dry connections, and identify failure modes to optimise future designs of timber-based modular structures.

2.2 Joint Response

The joint response is commonly determined by the shear interaction of vertical loading and frictional bearing capacities at the MT interface. As the connection is loaded vertically, the failure is governed by shear, which defines the joint's ultimate capacity. In

contrast, withdrawal (pull-out) loading, resistance is mobilised by the normal contact force arising from MT interference, generating frictional shear stresses that counteract removal. Cyclic assembly and reassembly modify this mechanism through surface wear and local crushing, leading to a progressive reduction in contact pressure and frictional resistance, as detailed later. Consequently, shear and cyclic responses quantify the degradation, MT joint stiffness, and the residual resistance.

To quantify the shear behaviour of the MT joint plated elements shown in Fig. 1c were manufactured. The setup assembles a CNC-cut, DIC-prepared central specimen (Fig. 1ci) with two extruding tenons (Fig. 1cii), which results in a 40 mm clearance from the base that allows vertical displacement of the central specimen under testing. For the shear tests, the testing procedure followed a displacement-control protocol at 1.0 mm/min via a 250 kN Instron machine, to allow the maximum compressive force to be reached within 180–420 s.

To assess degradation of MT joints under repeated assembly-disassembly, specimens consisting of plated elements shown in Fig. 1d were prepared. All CNC-cut specimens consist of a 20 mm long tenon specimen (Fig. 1di) and the base 20 mm deep mortise specimen (Fig. 1dii). The tenon specimens were clamped 40 mm into the Instron machine, and the base specimen was centred and fixed to the Instron via 4 bolts. Testing followed a 4-stage process: (1) 5 mm/min, displacement to –19 mm, to obtain the first cycle. (2) 5 mm/min, displacement to +9.5 mm to vertically centre tenon with mortise. (3) Cyclic testing at 5 Hz was selected to mimic the incision-removal behaviour and to obtain the penetration forces of each cycle until a plateau. (4) Loading rate: 20 mm/min, displacement: +9.5 mm to remove tenon from mortise.

Several methodological constraints bound the results. Material tests were limited to a single species (BPSP) and geometry; cyclic tests involved n = 5 specimens for the 20-cycle tests and n = 2 for the extended ~1000-cycle series, which is statistically limited.

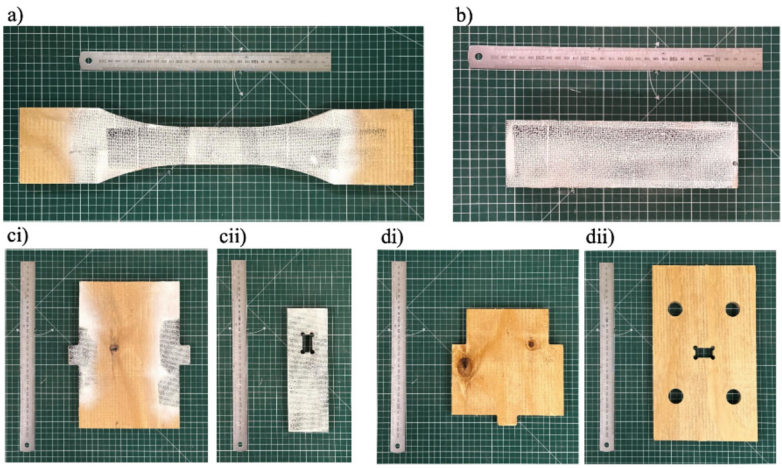


Fig. 1. CNC-cut material test specimen against a 30 cm ruler: a) tension (dog-bone), b) compression, c) MT shear connection, d) MT cyclic connection

The cyclic behaviour was evaluated only for MT friction without bearing between parts. The quantitative degradation trends should therefore be treated as indicative.

3 Results

3.1 Material Properties

For all tests, force-displacement curves from the testing machine and full-field images captured at a rate of 12 images/min were used for further analysis. Tensile tests assessed the BPSP's response under uniaxial loading, as shown in Fig. 2a and the representative image in Fig. 3a. The average ultimate tensile stress was 15.0 ± 1.76 MPa. The elastic region showed oscillations rather than a smooth slope because the DIC capture rate of 12 images per minute introduced gaps in the data. Over the full test, the oscillations evened out, resulting in a reliable Young's modulus (YM) data with a SD of ±1.02 GPa. Tension 3, which recorded the highest YM (5.27 GPa), exhibited a stepping failure with the stress dropping by 4 MPa, but it continued to deform until its second fracture point. Causes of failure include delamination, fibre tearing, and the natural heterogeneity of plywood layering.

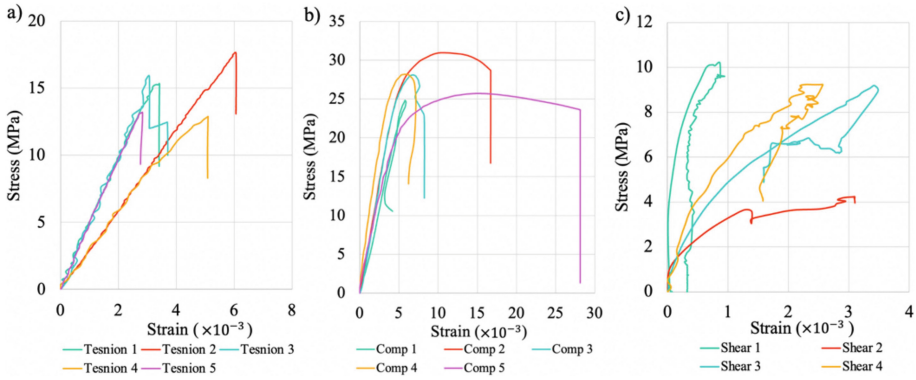


Fig. 2. Stress-strain curves for: a) tension, b) compression, c) shear connection specimens

Compression tests (Figs. 2b and 3b) found higher load capacities, with an average ultimate stress of 27.55 MPa (±2.15 MPa) and a YM of 5.18 GPa (±0.70 GPa). The 1.25 GPa difference between tensile and compressive moduli is consistent with the orthotropic, layered nature of plywood, where alternating face-grain and cross-grain veneers produce direction-dependent apparent stiffness in uniaxial tests [7].

Comp 1 exhibits snap-back behaviour, as the material momentarily loses load-bearing capacity, followed by a short recovery in displacement. This is due to delamination, shear plane failure, local buckling, or crack propagation. Localised crushing or progressive fibre buckling explains why Comp-2 and Comp-5 have a more ductile.

Shear results average ultimate shear stresses of 8.22 MPa (±2.32 MPa) and an average YM of 4.94 GPa (±0.84 GPa). All shear test specimens followed the same

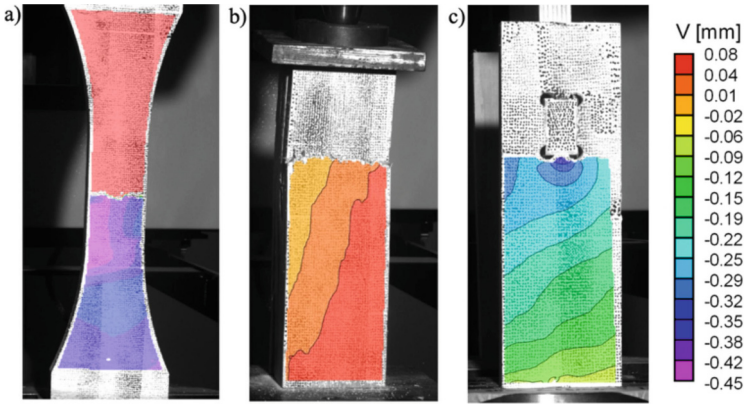


Fig. 3. Cyclic pull-out test data for samples subjected to a) 20 cycles, b) 1000 cycles

failure mode, with a splitting of the tenon that breaks away from the mortise plate and minute crushing of the mortise plate. Shear 1 achieved the highest stress and YM (10.20 MPa, 5.35 GPa). Shear 2 was an outlier, failing prematurely at 4.26 MPa – likely due to the loading rate being set too high, contributing to the higher standard deviation of ±2.32 MPa. Additional reasons include weak frictional interaction, prior micro-cracks from hammering during assembly, or localised crushing at the mortise wall. An average ultimate shear stress of 8.22 MPa indicated that the MT joints can resist moderate lateral forces before failure.

3.2 Repeated Assembly-Reassembly Response

The repeated assembly-reassembly tests include push-pull cycles of the tenon into the mortise. The tenon was pushed until its bottom part was in near contact with the bed of the machine, then then pull out at the upper face of the plywood base plate. This loading protocol engaged friction at the tenon-mortise interface, which degraded with increase in cycles. This is shown by the cycle-resistance degradation envelopes of the pull cycles only shown in Fig. 4. Note that the resistances for the push cycles were about 50% higher, but the degradation profile nearly identical. This degradation results from gradual compaction of the mortise walls and rounding of the tenon edges, which progressively reduces frictional resistance against withdrawal. The pull-out data were acquired for the first 20 cycles (Fig. 4a) and 1000 cycles (Fig. 4b), for five and two specimens, respectively. A maximum average pull-out force of 540.4 N (±74.16 N) and a minimum of 244.5 N (±72.9 N) were found, refer to Table 1. The variance is expected given the inherent plywood material characteristics.

Further tests were conducted to achieve a more sustained plateau in force readings, enabling a confident determination of the point at which the MT joint loses all friction-bearing capacity. Therefore, Cyclic 2 and Cyclic 3 were retested in the same manner, providing gradual force decay across ~1000 cycles. The representative decay in pull-out resistance over the number of cycles is illustrated in Fig. 4b, and the degradation of the MT joint is captured in Fig. 5. The residual pull-out forces were reduced to 55.14 N and

Table 1. Cyclic mortise and tenon data

Specimen ID	20 Cycles		1000 cycles
	Max. Force (N)	Min. Force (N)	Final Force (N)
Cyclic 1	540.3	366.1	–
Cyclic 2	476.0	244.6	55.1
Cyclic 3	558.6	317.2	128.1
Cyclic 4	668.0	467.8	–
Cyclic 5	458.3	329.6	–
Average ± SD	540.4 ± 74.2	345.1 ± 73.0	–

128.11 N, respectively, corresponding to 11% and 23% of their initial peak capacities, and to 23% and 40% of the capacity after 20 cycles. These values are based on n = 2 specimens and should be regarded as indicative of the degradation trend.

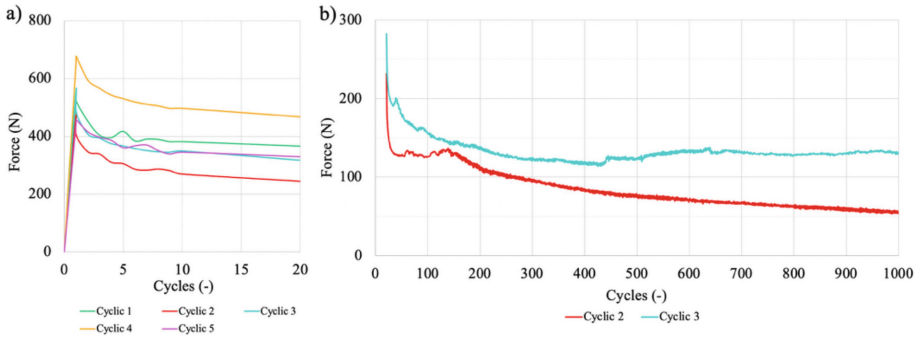


Fig. 4. Cyclic pull-out test data: a) cycles 0 to 20, b) cycles 21 to 1000

During retesting of the two specimens, the MT joint (Fig. 5) exhibited progressive surface wear, rounding of the tenon edges, fibre pull-out, surface abrasion, crushed fibres, and debris accumulation at the interface, which affected the pull-out readings. Cyclic 2 (Fig. 4b) exhibits spikes in force at cycle 145 and Cyclic 3 at cycles 440 and 640 due to the increased friction resistance given by the fallen debris into the mortise. However, the trend is that normal contact pressure steadily declines, explaining the rapid early drop followed by a slower decay toward a plateau.

3.3 Application to Timber Structures and Multiple-Life Reuse

At a conceptual level, for timber-timber joints used in temporary structures, structural performance beyond first use refers to the assessment of mechanical and functional performance after one or more cycles of assembly, service, disassembly, and reassembly. In such systems, repeated installation and dismantling, local embedment, and MT wear

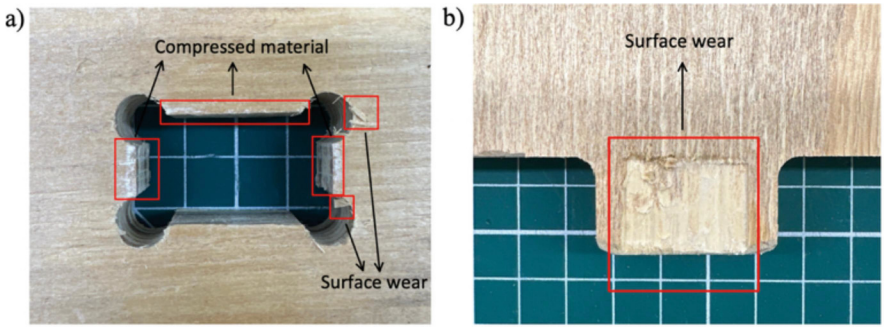


Fig. 5. Degraded cyclic specimen, Cyclic 2 after 1350 cycles: a) Mortise, b) Tenon

at contact interfaces progressively affect stiffness and strength, as indicated in (Fig. 4). Reuse across multiple lives therefore requires rigorous evaluation of the residual performance of both the timber members and, critically, the joints that govern load transfer and structural integrity. Conceptually, this may be represented as a sequence of beginning-of-life structural performance (BOLSP) and end-of-life structural performance (EOLSP) states across successive use cycles. Figure 6 illustrates the case of the MT joints tested under cyclic loading, correlating the conceptual PBSCE framework with the test results from this paper.

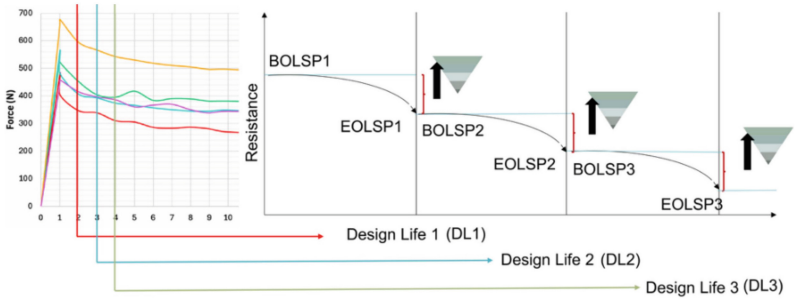


Fig. 6. Performance Based Circular Structural Engineering (PBSCE) framework for MT joints

An example is a modular arch comprising 252 mortise-and-tenon (MT) connections (Fig. 7). The arch was fabricated, assembled and tested under displacement control, reaching a maximum force of 26.0 kN before failure by tenon pull-out from the mortise along approximately one-third of the arch, following the thrust line. If resistance degradation is quantified through repeated assembly-disassembly tests on MT connections, the residual capacity of the structure can be estimated directly. For example, the average degradation of the five specimens in Fig. 4a indicates reductions of 27%, 32%, 35% and 37% after 5, 10, 15 and 20 disassembly cycles, respectively. These values provide a conceptual basis for estimating residual capacity over multiple lives, although further validation is required.

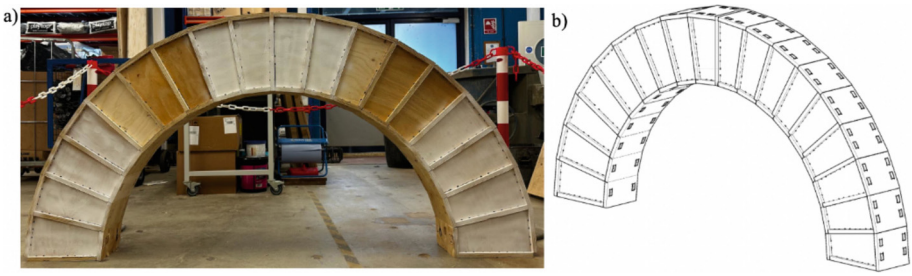


Fig. 7. a) Modular MT connected arch, b) 3D render

4 Concluding Remarks

Within the framework of Performance Based Circular Structural Engineering (PBCSE), this research examined how repeated assembly-reassembly affects the retained performance and reuse potential of CNC-fabricated dry mortise-and-tenon joints in Brazilian Pine structural plywood. The results showed that vertical load capacity is governed by combined shear and bearing actions, with failure defined by tenon splitting and local mortise crushing. Under repeated assembly cycles, pull-out resistance decreased as the interference fit progressively relaxed. At the first cycle, the average resistance was 540 N, reducing by 36% at 20 cycles and by 83% at ~1000 cycles. The main degradation mechanisms were: (i) damage of the mortise wall, (ii) wear and rounding of the tenon edges, and (iii) tolerance relaxation, with occasional local force increases caused by debris-induced frictional interlock. A modular arch was manufactured, assembled and tested under mechanical loading. Failure was governed by slip at the mortise-and-tenon connections, showing that focused connection-level testing is suitable for evaluating the assembly-reassembly capability of this structural typology. From a PBCSE perspective, the results show that reuse should be assessed through measurable retained performance rather than simple disassembly potential. Cyclic pull-out response, therefore, emerges as a practical reuse parameter for dry mortise-and-tenon joints, as it captures the progressive loss of friction and resistance over multiple lives. More broadly, the findings support a multi-life strategy for demountable timber systems, in which joints are classified according to residual performance thresholds rather than on binary reusable/non-reusable assumptions.

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Experimental Assessment of the Structural Reuse Potential of Reinforced Concrete Elements

Dan V. Bompa[1(✉)], Jack Schroeder[2], Adam Ozinsky[3], and Marco F. Funari[1]

[1] University of Surrey, Guildford GU2 7XH, UK
d.bompa@surrey.ac.uk
[2] Arup, London WIT 4BJ, UK
[3] 3XN GXN, London EC2A 4PS, UK

Abstract. A significant opportunity exists to move up the circular economy hierarchy by directly reusing structural elements from existing buildings, provided that rigorous and transparent assessment is undertaken. Within the wider remit of Performance Based Circular Structural Engineering (PBCSE) framework, which seeks to evaluate structural performance beyond first use and support evidence-based end-of-life decisions, this paper presents a case study for assessing the structural reuse of reinforced concrete. The investigation integrates geometry verification, non-destructive evaluation, material characterisation, and full-scale component testing to quantify structural response, serviceability behaviour, and governing failure modes. This included selective deconstruction and recovery of a full-scale cast-in-place reinforced concrete floor slab, followed by detailed laboratory testing. Experimental results showed that the reclaimed slab achieved an ultimate load capacity approximately 14 times greater than the design load required for an equivalent contemporary office floor, while serviceability performance remained acceptable at several multiples of the design service load. The results demonstrate that, when supported by a structured assessment and testing workflow, reclaimed reinforced concrete elements can meet or exceed modern structural performance requirements while delivering substantial environmental benefits. The study provides quantitative evidence to support reuse-led decision-making and illustrates how PBCSE can serve as an overarching framework for circular structural design.

Keywords: Performance Based Circular Structural Engineering · Structural reuse · Reinforced concrete · Experimental testing · Circular construction

1 Introduction

Recent research on circular construction has expanded rapidly, but the structural engineering dimension remains fragmented. Reviews of the circular economy in the built environment show that the literature is now mature in relation to definitions, end-of-life strategies and broad implementation barriers yet still lacks consistent methods for linking circularity decisions to residual structural performance, reliability and reuse qualification [1–3]. This gap is particularly important for structures because decisions

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on retention, reuse, remanufacture or recycling tend to depend on environmental indicators, but safety on the residual stiffness, strength, ductility, robustness and durability of components after their first service life. In this context, the concept of Performance Based Circular Structural Engineering (PBCSE) is proposed as a direction that integrates life-cycle assessment, structural mechanics and reliability-based decision-making to evaluate structural performance beyond first use.

For reinforced concrete, recent work has moved the field from precedent mapping towards design and experimental validation. A critical review of 77 reuse precedents established that the piecewise reuse of extracted concrete in new structures is technically possible and has a longer history than generally acknowledged [4]. More recent work has then shown how cut cast-in-place reinforced concrete slabs can be reused in new floor systems, with substantial reductions in upfront carbon while still satisfying structural requirements [5]. At the same time, the literature is beginning to adopt performance-based decision tools for concrete end-of-life management. The CirCrete framework is particularly relevant because it explicitly combines circularity strategies with technical and sustainability indicators to guide decisions on refurbishment, remanufacture and recycling of concrete structures [6]. For structural steel, the literature has progressed further on reuse protocols, logistics and environmental benefits, but less so on quantified residual performance assessment [7]. These developments are highly relevant, but they remain material-specific and do not yet amount to a unified structural framework across different component types and future use scenarios.

The emerging literature indicates that the field is shifting from circularity as a predominantly environmental or process-led discussion towards circularity as a problem of structural qualification and future performance. This transition creates a clear opportunity for PBCSE as a unifying framework. Such a framework would evaluate residual and future structural performance using evidence from inspection, non-destructive testing, material characterisation, experimental testing, modelling and reliability analysis, while also embedding circularity, traceability and design-for-future-reuse principles. Within the wider remit of PBCSE, this paper presents a case study for assessing the structural reuse of reinforced concrete.

2 Performance Based Circularity Approach

The life cycle of buildings and infrastructure may be described through a sequence of interrelated stages, beginning with the identification of need and strategic briefing, followed by conceptual design, detailed design, construction, operation, and end-of-life decision-making. The operational phase is typically the longest stage and often accounts for most of the asset's service life. At the end of operational use, the key question is no longer whether the structure has reached a nominal design age, but whether it remains fit for purpose, adaptable, and technically viable for continued use, partial retention, or recovery. Recent design frameworks emphasise the concept of "end of operational life" rather than "end of design life". This distinction recognises that many structures remain structurally sound even when they are no longer suitable for their original function.

A hierarchy of resource use provides a useful basis for prioritising interventions. At the top of the hierarchy is waste prevention, which includes avoiding unnecessary

construction and maximising the continued use of existing assets. This is followed by preparation for reuse and direct reuse of components, which retain the greatest proportion of embodied energy and structural value. Recycling occupies a lower position because, although it recovers material, it is energy intensive and often results in downgraded performance. Recovery and disposal represent the least desirable pathways. For buildings and infrastructure, this hierarchy implies that refurbishment, partial retention, and component reuse should be prioritised over demolition and recycling wherever technically feasible.

Structural performance beyond first use refers to the assessment of mechanical and functional performance after a component or asset has completed its initial service life. During operation, degradation mechanisms such as corrosion, fatigue, moisture damage, carbonation, chloride ingress, and material ageing may reduce stiffness, strength, ductility, robustness, and serviceability. Reuse therefore requires a rigorous evaluation of residual performance at the end of operational life. Conceptually, the problem may be represented as a sequence of "beginning of life structural performance" (BOLSP) and "end of life structural performance" (EOLSP) states across multiple design lives, where the central engineering challenge is to quantify the residual structural parameters that can be carried into the next use cycle (Fig. 1).

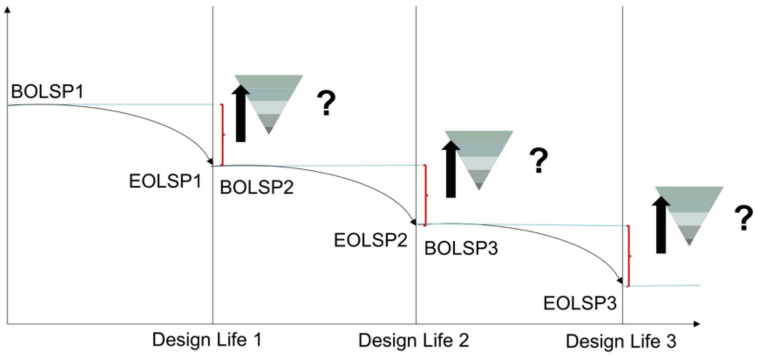


Fig. 1. Conceptual representation of PBCSE.

Building on the above, PBCSE may be defined as an overarching framework that integrates structural reliability, life cycle thinking, and circular economy principles to evaluate, retain, recover, and redeploy structural value across multiple lives. The aim is to develop evidence-based methods that support decisions on retention, refurbishment, reuse, upgrading, and end-of-life management using a combination of structural performance metrics, environmental indicators, and economic criteria. In practical terms, this includes: (i) physical inspection and visual assessment of existing assets; (ii) non-destructive testing and material characterisation; (iii) focused experimental testing of reclaimed components; (iv) analytical and numerical modelling of residual performance; (v) reliability-based assessment of capacity and uncertainty; and (vi) development of reuse-oriented design methods for both existing and future structures.

3 Selective Deconstruction and Testing

3.1 Case Study Background

The present study forms part of a broader circular construction initiative linked to the redevelopment of Euston Tower in London, in which the project team explored how the retained value of the existing structure could be increased beyond conventional demolition and downcycling routes. The wider redevelopment strategy retained the foundations and substantial parts of the core structure, corresponding to approximately 31% of the existing structure by volume, while also investigating whether selected floor elements could be harvested and reused in new structural applications [8]. Within this framework, a ribbed reinforced concrete floor slab was identified as a suitable candidate for recovery and structural evaluation. The concept was to cut discrete in-situ slab panels and reuse them as plank-type elements in a new building, thereby prototyping a high-value reuse route for concrete that would otherwise be crushed and recycled as aggregate [8]. The element was extracted from an existing office floorplate by selective deconstruction procedures intended to limit damage during removal (Fig. 2).

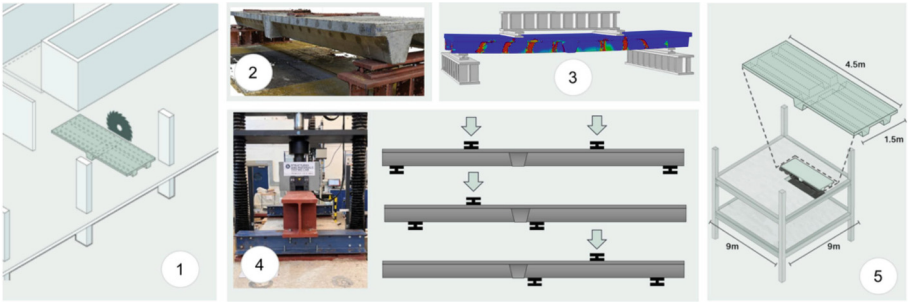


Fig. 2. Circular workflow for structural reuse: (1) site slab extraction; laboratory and numerical assessments (2) geometry [9], (3) nonlinear modelling, (4) selective testing; (5) slab reuse in a new structure (note: (1) & (5) by 3XN/GXN [8]).

A structured assessment workflow was developed to determine the suitability of the recovered element for structural reuse (Fig. 3). The preliminary stage involved estimating the likely structural capacity based on assumed material properties and reinforcement details, supported by sectional calculations and nonlinear modelling [10]. This was followed by geometry verification using direct measurements and photogrammetric survey techniques. Non-destructive investigations were then carried out to characterise the specimen, including ground-penetrating radar to identify the reinforcement layout, rebound hammer testing, and ultrasonic pulse velocity measurements to evaluate concrete quality. Material characterisation comprised estimation of concrete compressive strength from non-destructive correlations and tensile testing of extracted reinforcement bars. Structural response, which is the focus of this paper, was subsequently assessed by full-scale bending tests, including four-point bending to evaluate stiffness and serviceability-related behaviour and three-point bending to determine ultimate capacity and governing

failure modes. In the context of the wider project, this workflow also served as a prototype methodology for future qualification of reclaimed concrete panels prior to reuse in commercial developments [8].

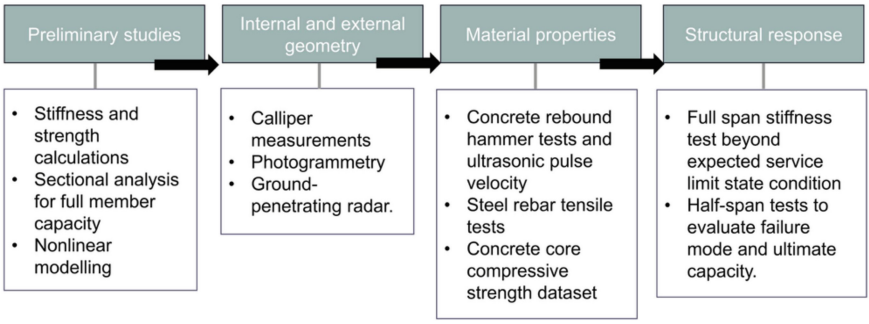


Fig. 3. Structural assessment procedure.

3.2 Experimental Programme

The panel extracted from the building had a width of 1210 mm and a length of 4517 mm. The floor was 270 mm thick, with the ribs 190 mm deep and the topping slab was 80 mm thick. Ribs were 140 mm wide at the bottom and 275 mm at the intersection with the slab. Ribs were spaced at 760 mm. There were three main square-twisted longitudinal bars in each rib which was one more per rib than expected. The two bottom bars were 33 mm/~1 ¼ in. square and the top middle bars were 27 mm/~1 in. square. Concrete cover to the bottom bars was 33 mm. A mesh was present in the topping slab with 5 mm bars spaced at around 153 mm, which was confirmed by ground penetration radar measurements. The extra reinforcing bars and thicker than expected concrete flange will result in enhanced strength. The slab arrived in good condition with a limited number of chips and cracks, which is to be expected for an element of its age. A transverse rib was present in the middle of the slab which was unreinforced. Non-destructive rebound hammer tests indicated that the concrete compressive strength is in the rage $f_{c,cube} = 49.1$ MPa, whilst the steel rebar properties were $f_{y,0.2\%} = 345$ MPa, for the proof strength and $f_u = 476$ MPa for the ultimate strength. Full-scale testing was conducted in displacement control in an Instron Satec frame with a 600 kN actuator. Three tests were performed. Test 1 used a full-span four-point bending arrangement to evaluate stiffness and serviceability-related response beyond flexural cracking (Fig. 4). Tests 2 and 3 used three-point bending on the two half-span specimens to evaluate the ultimate capacity and the main failure mode.

The load was transferred through a UC 305 × 305 × 198 steel beam and secondary loading beams; 40 mm rollers and 25 mm steel plates were used at both loading and support locations. Deformations were measured using the machine crosshead, 2–3 LVDTs, two string potentiometers, and two inclinometers. The LVDTs monitored rib displacements, the string potentiometers recorded mid-span flange deflections, and the inclinometers measured slab rotations near the support regions. All instruments were



Fig. 4. Image of the test slab in the rig.

calibrated before testing following standard laboratory procedures. The main results are shown in Fig. 5.

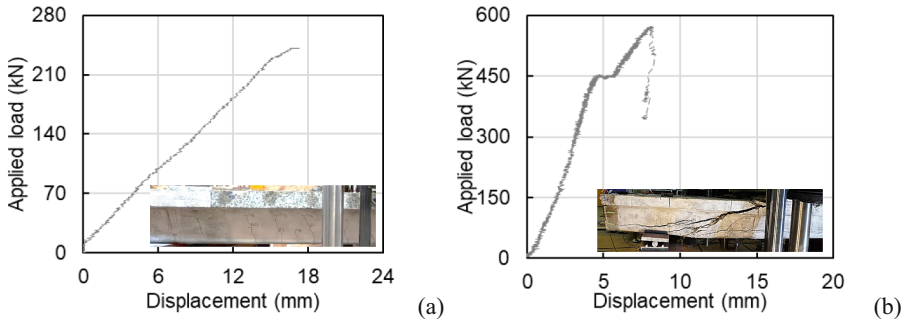


Fig. 5. Load displacement curves and crack details for (a) Test 1, (b) Test 2.

The full-span slab (Test 1) was tested under four-point bending in displacement control at 0.5 mm/min. The load-displacement response was broadly symmetric, with similar stiffness on both sides up to about 78 kN, after which limited softening was observed at one rib. Minor bedding-in effects were evident at low load, but the overall response remained largely linear up to the maximum applied load of 241.5 kN. Flexural cracking was first observed at about 31 kN, no shear cracking developed in any shear span, and all flexural cracks closed on unloading, indicating high stiffness and limited residual damage. The two half-span specimens were subsequently tested under three-point bending in displacement control. In both tests, loading was initially applied at 0.5 mm/min, reduced to 0.1 mm/min at the onset of shear cracking, and then increased again to 0.5 mm/min in the post-peak range to capture residual behaviour. In Test 2, after initial bedding-in up to about 150 kN, both ribs responded similarly until softening began at approximately 415–445 kN, corresponding to the onset of shear cracking; the peak load reached 571.9 kN, followed by widening of the governing diagonal crack and horizontal splitting at the level of the bottom reinforcement. Test 3 showed similar behaviour, with bedding-in at low load, comparable rib response beyond about 150 kN, shear crack initiation at about 405–435 kN, and a peak load of 537.7 kN, after which the

diagonal crack widened progressively in the post-peak range. In both tests, failure was governed by web shear.

In terms of design requirements for future reuse, the four-point bending tests indicated linear load-deflection response up to load levels exceeding those expected in service, highlighting that the recovered element retained substantial stiffness and structural integrity. The measured behaviour was consistent across the test configuration and confirmed the suitability of the slab under serviceability-related demand. Subsequent three-point bending tests produced a shear-governed failure at an average ultimate capacity of about 554.8 kN, with evidence of shear redistribution prior to failure. When expressed as an equivalent uniformly distributed action, the measured resistance corresponded to approximately 43 kN/m^2, significantly higher than that of a typical office floor design load of about 3 kN/m^2. These results indicate a substantial reserve of structural capacity relative to the intended reuse scenario. They also support the wider project claim that recovered in-situ concrete elements may provide technically credible alternatives to new precast-type components when appropriately assessed and detailed [8].

4 Concluding Remarks

This paper examined the structural reuse of reinforced concrete within the wider remit of Performance Based Circular Structural Engineering (PBCSE) framework, which aims to evaluate structural performance beyond first use and support evidence-based end-of-life decisions. A case study was presented in which a full-scale cast-in-place reinforced concrete floor slab was selectively deconstructed, recovered, and experimentally assessed to quantify the structural response. The main remarks are outlined below.

- Extraction of an in-situ reinforced concrete floor element from a central London building proved technically feasible, and the recovered slab met the structural performance requirements for reuse.
- A complete laboratory workflow was established for structural reuse assessment, combining geometry verification, non-destructive testing, material characterisation, analytical appraisal, and full-scale bending tests.
- The recovered element was in very good condition and exhibited substantial reserve capacity; four-point bending tests showed a largely linear response, while three-point bending tests produced shear-governed failure with an average capacity of 554.8 kN and evidence of shear redistribution.
- The measured resistance was well above the demand for a typical office floor application, confirming that the slab retained stiffness and strength beyond first use and could be assessed based on residual structural performance rather than assumed end-of-life value.
- The results indicate that reclaimed in-situ concrete floor elements may be reused in a manner analogous to precast plank systems, supporting higher-value retention of structural performance over conventional recycling and contributing to lower embodied carbon, reduced waste, and lower virgin material demand.
- Future work includes undertaking advanced nonlinear simulations and reliability-based assessments to evaluate structural performance beyond first use over a wider set of loading and material parameters representative for the second life scenario.

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Design for Disassembly in Interior Fit-Out: An n-Dimensional Classification of Dry and Prefabricated Systems for Circularity

Elisabetta Ginelli, Laura Daglio, Giulia Vignati(✉), and Alessandro Marco Greco

Politecnico di Milano, Milan, Italy
giulia.vignati@polimi.it

Abstract. The growing commitment of the construction sector to the transition toward a circular economy has led to multiple approaches defining current practices in the built environment. Among them, Design for Disassembly (DfD) and Design for Adaptability (DfA) play a central role, yet their widespread adoption is limited by costs, time management, and labor requirements associated with assembly and disassembly processes. This paper focuses on interior fit-out systems, a critical layer for circularity due to short life cycles and frequent layout changes. Despite extensive research on DfD at the building scale, studies on interior systems conceived as independent, prefabricated, and reusable subsystems remain limited. The paper examines macro categories of dry and prefabricated systems and introduces an n-dimensional classification – linear (1D), planar (2D), and spatial (3D) – to compare disassembly operations, labor needs, and adaptability potential. Findings highlight how dimensionality influences disassembly time, flexibility, and reuse, stressing the importance of integrating DfD and DfA from early design stages.

Keywords: Design for Disassembly · Design for Adaptability · Interior Fit-Out · Dry Construction Systems · Prefabrication · Reuse

1 Introduction. Design for Disassembly and Dry Construction Systems

The construction sector plays a significant role in the European economy, providing 18 million direct jobs and contributing approximately 9% to the EU GDP. Nevertheless, it remains one of the main drivers of resource consumption, environmental impacts, and waste generation. As of 2023, the buildings and construction sector accounts for approximately 32% of global final energy consumption and generates 34% of CO_2 emissions, including both operational phases and material-related contributions. Production chains remain heavily dependent on cement and steel, while construction and demolition waste in Europe still exceeds one-third of total waste streams [1]. The transition toward circular models requires the adoption of the circular economy as a guiding paradigm, supported

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by a comprehensive understanding of processes, practices, tools and methods for their integration across design, construction, and management phases [2]. Decisions regarding volumes, materials, and technical solutions defined at the early stages of design and planning strongly influence building performance during operation and, most critically, its transformability at the end-of-life stage. Rarely considered at this stage, however, is how buildings and their components can be dismantled or disassembled to reduce or minimize waste generation [3]. A key strategy for circularity is design for disassembly (DfD), i.e. designing to simplify disassembly, to enable the recovery of components and materials, improving their reuse potential and reintegrating them into future life cycles [4, 5].

Transitioning to a circular built environment requires moving beyond conventional construction techniques and a new design approach, by promoting dry construction methods, prefabrication, and off-site construction. According to the American Institute of Architects, the adoption of DfD is constrained by four main factors. First, economic considerations, as initial design costs may increase and investments in workforce training and materials may be required, although these costs typically decrease over time with accumulated experience. Second, shared design objectives and clear, precise communication are required among all stakeholders, along with a clear allocation of responsibilities. Third, market conditions must be considered, as local markets do not always support the temporary storage and subsequent reuse of recovered construction materials. Finally, the design approach itself must prioritize solutions that enable the future reuse of components and construction materials, ensuring a high degree of adaptability over time – an essential condition for supporting multiple transformations during the building lifecycle [6].

Based on these considerations, this study analyzes technological solutions that enable the progressive integration of DfD through stepwise strategies and applications. The study focuses on partitioning and interior fit-out systems – referred to as the infill layer in the Open Building framework [7] – comprising elements such as partition walls, finishes, secondary systems, and internal divisions. These components typically exhibit short- to medium-term life cycles, are subject to frequent changes, and are directly related to user needs and activities.

Interior partitioning and fit-out systems represent the building layer most frequently modified, whether for layout reconfiguration to accommodate different functions over time [8] or for immediate convertibility of space (adjustability, versatility) [9]. Compared with structural systems, interior fit-out components have shorter life cycles and generate disproportionate amounts of waste [10], often limited to 5–15 years, particularly in office or retail buildings. Furthermore, interior systems generally have lower performance requirements, as they do not require strict control of thermal insulation or air- and water-tightness, simplifying their design and application. Despite a substantial body of research on Design for Disassembly, Adaptability, and Prefabrication at the building scale, peer-reviewed studies focusing specifically on interior fit-out systems as independent, prefabricated, and circular subsystems remain scarce.

Through the analysis of macro-categories of dry and prefabricated construction systems currently available on the market, this study introduces the n-dimensional variable of construction elements as an analytical tool for classifying design solutions, with the

aim of identifying their strengths and limitations. This approach is innovative in that it reframes existing dry and prefabricated systems through a unified geometric perspective, enabling a direct comparison of assembly logic, disassembly performance, and reuse potential across different scales of intervention.

2 Toward an n-Dimensional Classification of Fit-Out Systems

To understand the limitations and potential of the transition toward circular interior design, this study investigates products, systems, and components currently available on the international market. Dry and reversible connection solutions for interior partitioning and finishes were analyzed, revealing a growing market characterized by a drive for innovation in response to increasing demand for DfD, also following the emergence of European guidelines and regulations at both international and European scales [11, 12]. Academic, design, and industrial research on the industrialization of interior systems has accumulated a significant body of experimentation throughout the 20th century, particularly in the post-war period, within a broader interest in prefabrication in the construction sector [13]. However, these efforts have had limited impact on mainstream construction practices. This work primarily concerns off-site systems, as well as dry-assembly solutions where partitions are often integrated with furnishings to form system-based assemblies of modular, reusable components. While dry assembly enables reversibility at the connection level, prefabrication operationalizes this logic through standardized, off-site manufactured systems.

Building on classification proposals derived from prefabricated construction [14] and historical and spatial-functional analyses of interior [15], this study proposes a geometric categorization of systems that both integrates and surpasses the ambiguous distinction between dry assembly and prefabrication. In particular, the study reflects on the potential and barriers of different systems from a design perspective, extending to building transformability and component reuse.

The efficiency and feasibility of applying DfD principles are intrinsically de-pendent on the dimensional scale of the adopted construction elements. The concept of classification based on the n-dimensional variable – defined according to the morphology of the technical elements employed (i.e., 1D, 2D, or 3D) and the scope of actions and complexity during assembly, disassembly, and reuse - provides a useful framework to understand how the geometric multidimensionality of construction elements influences disassembly time, labor requirements, and spatial adaptability. From a DfA and DfD perspective, the greater the n-dimensional variable of the construction element, the shorter the potential on-site disassembly time. Conversely, the greater the n-dimensional variable, the lower the flexibility of the element for future reuse cycles.

Based on these considerations, it is therefore possible to categorize elements into three main morphological models, which summarize existing dry-assembly and prefabricated interior solutions, as well as emerging innovative systems on the market (Table 1).

Table 1. The n-Dimensional Classification of Fit-Out Systems.

	Level of prefabrication Labor intensity Level of flexibility fabrication		
Geometrical category	LINEAR Low (on-site assembly)	PLANAR Medium (panelized prefabrication)	SPATIAL High (off-site volumetric)
Example	Stud-and-rail partition with infill panels (gypsum/timber drywalls and ceilings, etc.)	Stud-and-rail partition with finished infill panels (drywalls, modular suspended ceilings, access floors, etc.)	Prefabricated bathrooms and systems, booths
Technology The manufactured system requires the definition of the (interfaces between different fit-out subsystems)	On-site customized interface	off the shelf system + possible special or on-site interfaces	juxtaposition (+ service connections)
Performance (acoustics, fire resistance, etc, depend on the manufactured system and on its interfaces with the other fit-out subsystems)	varies according to the on-site assembly and interfaces	varies according to the interfaces	totally off-site controlled
Design strategies Spatial layout requires specific measures for application of the construction systems for disassembly	free	modular coordination (flexibility depends on modules size)	free plan with functionally predefined spatial zones (served and servant spaces)
Disassembly for Adaptability The construction systems are reused locally	disposal and new construction low initial cost, high costs for refit with waste generation	high initial cost offset through the reuse of components	low customization
Disassembly for Reuse The construction systems are relocated	limited reuse potential	minimum transportation and handling issues related to spatial constraints and finish overlaps (including relocation and potential panel replacement) possibility of product system service purchase durability of components and joints guarantee reuse	transportation and handling issues low customization durability/fragility

2.1 Linear Model (1D) Discrete Components for Traditional Dry-Assembly Systems

The Linear Model includes all dry-assembly systems, such as partition walls, suspended ceilings made of gypsum or wood-composite panels with internal frameworks of cold-formed steel profiles or timber, which together form a system of linear elements with limited modularity. These elements are subsequently infilled with panels cut to size on-site, adapting to the framework geometry and offering spatial flexibility. Linear systems are widely used and offer a high degree of adaptability to interior contexts. However, their installation requires considerable on-site labor, particularly for finishing operations, which can sometimes compromise reversibility (i.e., joint plastering) and limit reuse potential.

Despite the possibility of partial disassembly, these elements are mainly recoverable only for disposal, and their adaptability depends largely on the simplicity of removal rather than inherent system flexibility.

Key advantages of linear systems include ease of storage and low material costs. Nevertheless, on-site assembly demands significant labor for both inter-element connections and interfaces between different systems, which directly affects the final performance of the installation. Reversibility is limited, and although the system allows some flexibility in layout modifications, it remains constrained compared with more modular or prefabricated alternatives.

2.2 Planar Model (2D): Modular Systems for Reversible Partitions

The Planar Model refers to more advanced solutions compared with linear systems, consisting of metal frameworks with simplified locking mechanisms and prefabricated panels that form a modular planar partition system. These systems significantly reduce assembly and disassembly time compared with traditional linear solutions, enabling integration with furniture (which can become part of the system) and mobile solutions such as retractable or foldable walls. Although the initial material cost of these systems is higher, this investment can be offset over time, as the same components can be reused for layout reconfigurations, providing economic and environmental benefits. The durability and ease of transport and assembly further support reuse in other contexts, opening opportunities for Product-Service System (PSS) models.

From a design and sustainability perspective, careful attention to interface detailing during on-site installation is critical to ensure high environmental performance. Designers are encouraged to preconfigure potential layouts to minimize intervention requirements and reduce the impact of future rearrangements. Overall, the Planar Model combines flexibility, modularity, and reuse potential, representing a significant step toward the practical application of circular principles in interior fit-out systems.

2.3 Spatial Model (3D): Prefabricated Volumetric Modules

The Spatial Model represents the highest level of prefabrication, employing three-dimensional modules that are partially or fully finished in the factory and then transported to the site. This approach drastically reduces on-site construction time, allowing rapid

assembly and disassembly on a large scale. Despite substantial operational efficiency and the near-elimination of on-site labor, the Spatial Model presents significant challenges, including high logistical costs associated with transporting large volumes and the need for heavy equipment to maneuver modules on-site. Functional modules often define the character of interior spaces, such as movable units on wheels or tracks, or wet-space modules (i.e., bathrooms or kitchens), which may constitute the only rigid elements in the spatial system.

The high degree of customization during initial fabrication can limit flexibility for subsequent layout reconfigurations or reuse in other contexts, representing a potential barrier for adaptive interior design. Nonetheless, for certain building types – such as healthcare, hospitality facilities and collective housing – the Spatial Model can achieve cost efficiencies through economies of scale. Proper organizational strategies for layout zoning (i.e., served and servant spaces) further support long-term adaptability. The Spatial Model prioritizes efficiency and speed of installation, with high initial investment and logistical requirements, but it offers considerable potential for large-scale prefabrication and circular interior design when integrated with careful planning and modular strategies.

3 Discussion: Design Implications of the n-Dimensional Variable for DfD

DfD requires confronting the n-dimensional nature of construction elements. This reflection does not constrain the designer's scope of action, but it seeks to guide the design process toward greater awareness in the strategic integration of each n-dimensional model in alignment with the objectives and requirements of each phase of the building's life cycle. Labor intensity, which is inversely proportional to the degree of prefabrication and directly proportional to system flexibility, affects the economic variable that has traditionally represented a barrier to the adoption of disassemblable systems.

Linear systems offer low material costs and moderate on-site labor requirements, but their performance is limited by labor-intensive assembly. While these systems provide the highest degree of interior adaptability, their potential for implementation within a circular economy framework is limited. Reversible adhesive-based interfaces may provide some flexibility, but the natural evolution toward reuse and easy transformability is most evident in the planar system.

For planar systems, the initial material cost is higher, despite minimal labor requirements due to mechanical simplicity and lightweight materials. However, this cost should be evaluated not only during initial construction but also in terms of layout reconfiguration and potential reuse, representing an investment that can be amortized over time. This is achievable when the design paradigm anticipates multiple spatial configurations over time, guided by modular grids, appropriate positioning of vertical service cores, and a structural system designed to minimize subsequent interventions. The high degree of reuse and flexibility of planar systems also makes them suitable for advanced commercial models, such as Product-Service Systems (PSS), which transition from physical goods to services and allow control over component end-of-life.

Three-dimensional systems, which are more complex to fabricate and transport, involve higher costs that can be mitigated through economies of scale, particularly in high-density building types such as healthcare facilities, hospitality buildings, and collective housing. In these cases, clear organizational strategies for functional zoning (served and servant spaces) support long-term adaptability with respect to unit size and separation. Conversely, in other typologies, such as commercial buildings that require large, highly adaptable spaces only partially influenced by natural daylight and with deep building volumes, a smaller-scale system is necessary to ensure versatility. Anticipating design decisions implies a paradigm shift in which each operation of the disassembly process must be addressed from the earliest design stages.

This anticipatory approach entails the obligation to plan assembly and disassembly procedures for every construction element. Through such design strategies, it becomes possible to overcome the current barriers to DfD previously identified.

4 Conclusion: Design and Production

From a Design for Manufacturing, Assembly, and Disassembly (DfMAD) perspective [16], the analysis of these systems highlights a paradigm shift that maximizes system benefits through modular design, zoned adaptability, suitability of building typologies, anticipation of future transformations, and a reconsideration of construction costs from a life-cycle perspective. This shift should guide designers toward a more integrated and systemic approach, in which the building, interior spaces, and equipment/furnishings are conceived as parts of a unified design process that involves all stakeholders in the construction sector, supported by the emerging regulatory framework. On the other hand, there are implementation and development perspectives for the systems themselves, particularly regarding planar and spatial systems, which represent the most promising avenue toward circular economy adoption.

For planar systems, the focus should not be solely on further increasing already high performance, customization, or versatility. Rather, emphasis should be placed on implementing adaptability features that allow integration of equipment and service cores [17]. Additionally, a limitation to adaptability lies in interface design, which requires renewed attention [18] to ensure high acoustic performance and fire safety. In this regard, digital transformation offers opportunities for developing off-site customized nodes, tailored on a case-by-case basis according to site-specific conditions. For prefabricated volumetric modules, development should move beyond the conventional wet-block approach toward creating ancillary spaces with varied functionality, potential mobility, and transformability, advancing the concept of “box-in-a-box” within a neutral spatial framework.

These considerations open interesting perspectives for both component and interior design, emphasizing the need for synergy between production and design disciplines and greater awareness within the real estate sector.

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The Adaptive Skin: Circular Design Strategies for the Regeneration of Existing Buildings

Monica Cannaviello(✉) and Maria Gelvi

University of Campania "L. Vanvitelli", 81100 Caserta, Italy
monica.cannaviello@unicampania.it

Abstract. The regeneration of the existing built environment requires a reconfiguration of the relationship between building envelopes, material cycles, and architectural form, shifting the façade from a static boundary to an adaptive and circular system, designed to meet not only current needs but also future ones. This paper investigates how material choices and circular design applied to the building envelope can contribute to the sustainable regeneration of existing buildings, by extending their life cycle, improving environmental performance, and reducing embodied and operational emissions. The research adopts a systemic and multidisciplinary methodology that combines a literature review on circularity integration criteria in façades with a comparative analysis of relevant case studies. The paper outlines a methodological framework in which circularity is not treated as a purely technical add-on, but as a generative driver for architectural form, supporting renovation strategies that improve thermal performance, reduce resource consumption, and support low-carbon regeneration processes.

Keywords: Building envelope · Circular principles · Deep Renovation · Compositional dimension · Environmental dimension

1 Introduction

In contemporary architectural debate, the concept of the 'second skin' has gradually come to play a central role in redefining the relationship between architecture, the environment, and the home. In a context marked by the urgency of climate issues and the decarbonisation targets for the construction sector, the building envelope has emerged as one of the primary means through which architecture can simultaneously influence energy performance, the quality of the living space, and the reduction of environmental impacts throughout a building's life cycle. The gradual introduction of increasingly stringent energy standards has brought the envelope's role in regulating indoor environmental conditions back to the forefront of architectural design—a role that, in the era of modern architecture, had been delegated to mechanical and building services systems. Contemporary thinking has once again recognised architecture itself as playing an active role in environmental mediation. From this perspective, the façade ceases to be interpreted as a simple element separating the interior from the exterior, instead becomes a complex system that integrates climatic, spatial, and perceptual dimensions, assuming the form of a layered membrane capable of mediating between domestic space and the environment.

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At the same time, the growing focus on the embodied carbon emissions of building materials and processes [1] has prompted architectural research to examine environmental impacts across the life cycle of building materials and components. In this context, the circular economy paradigm proposes a shift away from traditional linear models, promoting strategies focused on reducing resource use, extending the service life of building systems, and reintroducing materials into production cycles. Given that approximately 85–95% of Europe's building stock that will be in use by 2050 has already been built, the refurbishment of the existing built environment represents one of the main challenges for the ecological transition of the construction sector. In this context, deep renovation projects play a strategic role in reducing carbon emissions and improving the quality of living, with the building envelope identified as one of the main areas for intervention [2].

However, interventions on the building envelope cannot be interpreted purely as energy efficiency measures; rather, they require a balance between thermal performance, the quality of the architectural space, and the environmental impact of the materials. Despite the growing interest in adaptive façades and circular design strategies, the literature still tends to treat these two areas as distinct fields of research: on the one hand, studies on adaptive façades focus primarily on technological and performance aspects; on the other, research on the circular economy analyses mainly material cycles and resource management. Less explored, however, is the architectural and compositional dimension of these strategies, namely how the principles of circularity can translate into new ways of designing the building envelope and contribute to the construction of architectural form. The contribution of this research lies in proposing an integrated interpretation of the adaptive façade as a compositional device and a circular design strategy. From this perspective, the second skin is interpreted not merely as a technological system for improving energy performance, but as an architectural interface capable of reconfiguring the relationship between the existing building, material cycles, and the construction of the inhabited space. Through the design of the building envelope, the principles of the circular economy can thus be translated into architectural strategies that extend the useful life of buildings, reducing resource consumption, and activating new cycles of transformation within the built environment.

2 Methodological Approach

Starting from the theoretical premises outlined above, this research interprets the façade as an adaptive skin, that is, as a compositional and technological device capable of reimagining the existing built fabric as a dynamic field of transformation. From this perspective, the architectural envelope is not considered solely as a technical element, but as a multi-level interface through which the architectural organism mediates interiority and exteriority, permanence and transformation, memory and future projection. The building envelope thus becomes the point of convergence between the existing structure and new performance requirements, between energy efficiency and the quality of the living space, as well as between operational emissions and emissions embedded in the materials. The design of the second skin, therefore, plays a strategic role in the processes of transforming existing architecture, emerging as one of the key areas through which environmental, performance, and compositional objectives can be integrated. The research

adopts a systemic and multidisciplinary methodology, combining a critical review of the literature on adaptive façades and circular design strategies with a comparative analysis of case studies in which the introduction of a second skin represents a strategy for the redevelopment of the building envelope. Building on the resource cycles optimisation strategies developed by [3] and subsequently developed by [4], the research investigates how adaptive façades can contribute to the implementation of circular design principles in relation to four main strategies:

- *Narrowing*: reducing resource use;
- *Slowing*: extending the useful life of materials, components, and buildings;
- *Closing*: closing production cycles through the reuse and recycling of materials;
- *Regenerating*: using renewable materials and strategies that contribute to ecosystem regeneration.

Through this analytical framework, the research explores how the 'second skin' can serve as a point of convergence between principles of circularity and the construction of architectural form, transforming interventions on the building envelope into a strategy capable of combining environmental performance, resource management and the regeneration of the built environment.

3 Circular Design Strategies and Adaptive Façades

The circular economy paradigm proposes a radical shift away from the traditional linear models of the construction sector, which are based on a cycle involving the extraction of resources (*take*), the construction of buildings (*make*), and their subsequent decommissioning or demolition (*dispose*). In contrast, the circular approach aims to keep materials, components, and building systems in use for as long as possible, thereby preserving their value and reducing the need for new resources. In the context of regenerating the built environment, this shift implies a fundamental rethinking of design principles. Renovations to existing buildings cannot be viewed merely as technological upgrades but must become a process able to activate new life cycles for buildings and the materials from which they are constructed. From this perspective, the building envelope takes on a strategic role. The façade is, in fact, the element through which architecture can simultaneously influence the building's environmental performance, the quality of the living space and the durability of the building systems. Among the possible intervention strategies, the introduction of an adaptive second skin emerges as one of the most effective solutions for combining the requirements of energy efficiency, spatial transformation and material circularity. The layering of the building envelope makes it possible to improve the building's environmental performance without making invasive alterations to the existing structure, whilst at the same time creating new intermediate spaces that expand the possibilities for living. Several studies [3, 5, 6] have highlighted that, to contribute significantly to reducing environmental impacts in the construction sector, it is necessary to implement four main principles for optimising resource cycles: narrowing, slowing, closing, and regenerating. Each of these principles can be translated into specific design solutions within the context of adaptive façades, generating architectural solutions that integrate technological and compositional dimensions.

3.1 Narrowing

The 'narrowing' strategy primarily focuses on reducing resource consumption through a more efficient use of materials and energy. In the case of adaptive façades, this strategy translates into the building envelope's ability to optimise the building's energy performance during the operational phase. The second skin can, in fact, operate as a system for modulating climatic and microclimatic factors, helping to improve energy performance and comfort levels. Ventilated air gaps, adjustable shading devices, louvres, and filter screens are bioclimatic design elements that, if properly integrated into the architectural design, can significantly influence the building's energy balance. From an architectural perspective, such devices do not merely function in terms of performance but also introduce a new compositional depth to the building envelope. The façade thus becomes a layered structure capable of transforming the relationship between the building and its surroundings. A significant example is provided by Kengo Kuma's residential architecture, where the building envelope is often conceived as a sequence of filters consisting of wooden slats or permeable screens that control solar radiation and natural ventilation. Similarly, in the Moriyama House in Tokyo (SANAA, 2005), the lightness of the building envelope and the fragmentation of the volumes create a sense of porosity that allows light and air to pass through the architecture, demonstrating how energy consumption can be reduced through spatial and compositional strategies as well.

3.2 Slowing

The 'slowing' strategy focuses on extending the service life of materials, components, and the buildings themselves in order to avoid demolition and replacement. From this perspective, the 'second skin' is one of the most effective methods for regenerating existing buildings, as it allows the building's environmental performance to be upgraded without altering its load-bearing structure, transforming the regeneration project into an incremental process. A prime example is the transformation of the Tour Bois-le-Prêtre in Paris (Lacaton & Vassal with Frédéric Druot, 2011), where the addition of deep balconies and climate-controlled conservatories envelops the existing building, expanding the living spaces and improving its energy performance. The façade thus becomes an intermediate space that can increase the quality of life and extend the building's lifespan. Similar strategies were also adopted in the redevelopment project for the Grand Parc Bordeaux (Lacaton & Vassal, Druot and Hutin, 2017), where the introduction of greenhouses and deep balconies radically transformed the spatial and environmental conditions of the dwellings without resorting to demolition. In these interventions, the second skin acts as a tool that can activate regeneration processes based on the continuity and transformation of the built environment.

3.3 Closing

The closing strategy involves reintroducing building materials and components into production cycles through reuse and recycling practices. In the case of adaptive façades, this approach means using modular, demountable components, designed according to the principles of 'design for disassembly' [7], which allow for the replacement, reuse and

relocation of materials over time. The building envelope thus becomes part of a circular system capable of reducing waste production and extending the life cycle of building components. A significant example is the Resource Rows project in Copenhagen (Lendager Group, 2018), in which the building envelope is constructed using bricks recovered from demolished buildings. In this case, the reuse of materials is not merely a technical choice, but becomes an integral part of the architectural composition, transforming the material memory of the built environment into a generative element of the façade. Further developments of this approach are evident in experimental projects such as Circle House (BIG, GXN, 3XN, 2020), conceived according to systematic principles of circularity and designed to be disassembled and reassembled using modular prefabricated systems. Similar experiments can be found in the work of Superuse Studios, such as in Villa Welpeloo (2009), where the building envelope is constructed using reused industrial recovered components. In these cases, circularity is not limited to the management of materials, but becomes a principle capable of generating new architectural configurations.

3.4 Regenerating

The regenerative strategy involves the use of renewable materials and design solutions capable of contributing to ecosystems' regeneration. In the case of adaptive façades, this approach translates into the integration of bio-based materials, vegetation systems, and devices designed to improve the microclimatic conditions of buildings and urban spaces. A prime example is Stefano Boeri's Bosco Verticale in Milan (2014), where the façade incorporates layered vegetation capable of contributing to microclimatic regulation through shading, air filtration, and the mitigation of the urban heat island effect, transforming the building envelope into an active ecological system—although not without its challenges in terms of economic sustainability. A further experiment is represented by the BIQ House in Hamburg (Splitterwerk and Arup, 2013), in which the building envelope incorporates bioreactor panels containing microalgae that can produce biomass and contribute to the building's energy regulation [8]. Similarly, in the residential architecture of the WOHA studio in Singapore, the building envelope often takes the form of a multi-level ecological system in which vegetation, shading, and natural ventilation combine to create living spaces capable of actively interacting with the climate.

4 The Second Skin's Dimensions

4.1 Compositional Dimension

From an architectural perspective, the second skin represents a design field in which the construction of form and the logic of transforming the built environment converge, redefining the role of the building envelope in shaping the inhabited space. The introduction of an adaptive skin effectively transforms the façade from a simple boundary between interior and exterior into a layered spatial threshold capable of creating depth, regulating the climate, and establishing new relationships between architecture and landscape. From this perspective, the second skin operates through three main compositional dimensions: the depth of the architectural space, the modulation of atmospheric conditions, and the shaping of the building's form.

The first dimension concerns the introduction of a habitable depth within the building envelope. Whilst a significant part of modern architecture reduced the façade to a thin surface, the layered envelope restores a thickness to the architectural threshold capable of mediating between domestic space and the external environment, introducing intermediate spaces that expand the conditions of living.

The second dimension concerns the modulation of atmospheric conditions—light, air, and solar radiation—which, through filters and shading systems, become constituent elements of the quality of architectural space and contribute to the building's climate regulation.

The third dimension concerns the construction of the architectural form. Shading systems, grilles or slats transform the façade into an articulated surface capable of generating rhythm, depth and perceptual variations, contributing to the definition of the building's formal identity.

4.2 Environmental Dimension

The three compositional dimensions identified converge in the definition of a broader environmental dimension of the building envelope.

In the contemporary context, marked by climate and energy challenges, the second skin takes on an infrastructural dimension, emerging as one of the principal mechanisms through which architecture mediates the relationships between the building, the environment, and resource cycles. As Kenneth Frampton [9] observes, the architectural project is called upon to engage with the specific conditions of climate and place, integrating technology and form in the construction of space.

From this perspective, scholars such as David Leatherbarrow [10, 11] and Michael Hensel [12, 13] have highlighted how architecture can be interpreted as a dynamic system of interaction between building and environment, in which the envelope plays a central role in mediating the flows of light, air, and energy.

The second skin thus emerges as a device capable of integrating environmental dimensions and architectural composition.

The façade therefore becomes a habitable threshold, a mediating structure between domestic space, the city, and the landscape. From this perspective, the second skin represents not merely a technological solution but a new grammar of the building envelope, through which contemporary architecture explores forms of habitation that are more porous, adaptive, and responsive to environmental conditions.

5 Towards a New Grammar of the Building Envelope

The analysis of the case studies highlights how adaptive façades can serve as one of the key devices for operationally translating the principles of circular design into architectural projects. The strategies of narrowing, slowing, closing, and regenerating find a prime area of application in the design of the building envelope, enabling a reduction in resource consumption, an extension of buildings' service life, and the reactivation of material cycles (Fig. 1).

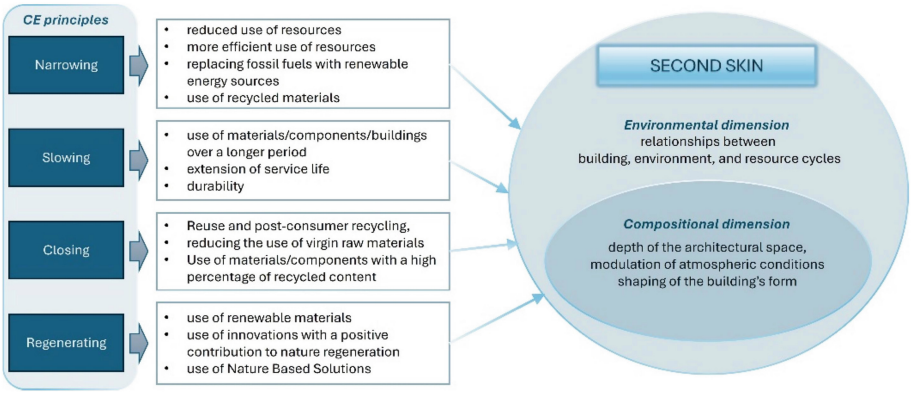


Fig. 1. Circular design principles for second skin.

Although some of the examples shown relate to new-build projects, the design solutions employed can also offer interesting ideas for the refurbishment of existing buildings. From this perspective, the building envelope emerges not merely as a technical device for improving energy performance but as an element able to integrate environmental, structural, and compositional aspects. The multi-layered façade introduces intermediate spaces that mediate the relationship between interior and exterior, improve the building's thermal performance, and enhance the living environment.

The second skin thus becomes a critical interface between the existing building, the environment, and material cycles, through which the regeneration project can simultaneously work to reduce energy consumption, extend the building's lifespan, and circularly manage resources.

In this context, the multi-layered façade represents not merely a technological upgrade of the building envelope, but a new grammar of regeneration. Through the second skin, the circularity of materials and the construction of the architectural form converge in a design paradigm in which the transformation of the built environment becomes an opportunity to rethink architecture as an open system of relationships between space, climate, and material cycles.

It should, however, be noted that architectural projects are often not accompanied by life-cycle assessments that allow their environmental benefits and impacts to be assessed. With a view to the ecological transition of the construction sector, such assessments should instead be made available to the public to promote greater transparency. Future research should aim to quantify the actual benefits associated with the use of adaptive façades in terms of decarbonisation potential, both during the design phase and once the building has been constructed.

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A Hierarchical Structural Documentation Framework for Modular Timber Structures Using Structural Component Passports Toward Circular Construction

László Mangliár(✉), Jiayi Li, and Lars Vabbersgaard Andersen

Civil and Architectural Engineering Department, Aarhus University, Aarhus, Denmark
lm@cae.au.dk

Abstract. Modular timber construction offers a strong potential for circularity, but structural engineering workflows remain project-specific, documenting modular buildings as conventional assemblies of individual members. Structural verification is repeated for each project, and structural information is not retained in a transferable form that would enable component reuse. This paper proposes a hierarchical structural documentation framework that reorganises verification and documentation across building, component, and connection levels. The framework combines reduced-order modelling with code-compliant capacity envelopes to generate a structural component passport containing certified performance and lifecycle information. A portal frame case exemplifies the approach compared to a conventional documentation workflow and shows how reusable structural performance data can support traceability, reduce repetitive engineering effort, and enable structural reuse.

Keywords: Modular Timber Structures · Structural Documentation · Reduced Order Modelling · Circular Construction · Structural Reuse · Structural Design

1 Introduction

Modular timber construction offers a pathway to high-value component reuse through efficient fabrication and design for disassembly, while timber inherently minimises embodied carbon [1, 2]. However, whereas modularity facilitates manufacturing, construction, and development, the structural engineering practice supporting it remains largely linear [3]. The current documentation process sees modular buildings as assemblies of individual members rather than considering the structural performance of the modules. This requires repetitive verification, and once the modules are assembled, their performance data are effectively lost and cannot be reused in other projects, even if the modules are the same.

The inability to transfer reliable structural information across similar projects and multiple life cycles is a critical barrier to the circular economy. To resolve this, the paper proposes a hierarchical structural documentation framework that decouples verification

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from individual projects. By utilizing substructure analysis and code-compliant capacity envelopes, we generate a structural component passport (SCP), including a condensed stiffness matrix and pre-certified safety domains, providing modules with a permanent structural identity, enabling immediate re-integration and re-verification in secondary life cycles or across similar construction projects.

The workflow is validated by a 10 m × 4 m portal frame case study, demonstrating how pre-certified structural data enables seamless component reuse and provides the digital infrastructure required for high-value circular timber construction.

The paper is structured as follows: Sect. 2 introduces the concept, and Sect. 3 describes the methodology as well as the case used for illustration of the workflow. Results and analysis of the case study can be found in Sect. 4, while Sect. 5 provides a discussion of the implications and limitations, and Sect. 6 lists the main conclusions.

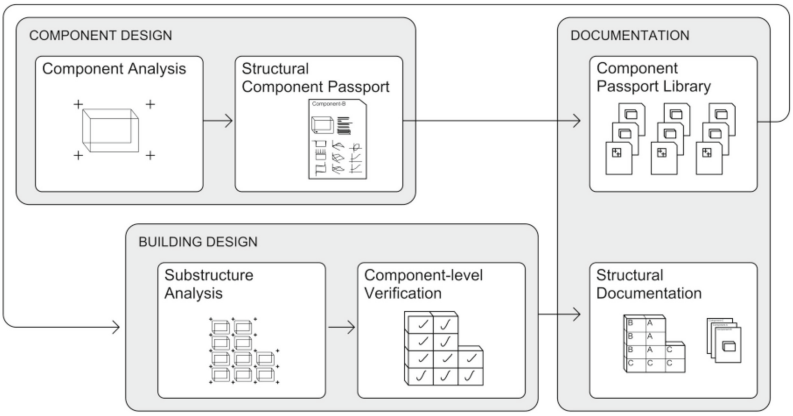


Fig. 1. A hierarchical structural documentation framework, workflow diagram.

2 Background and Concept of the Framework

Today's engineering practice creates a "documentation lock-in" where structural performance data is valid only for a single building context. Once the modules are assembled, their structural identity is lost, making high-value recirculation technically unfeasible due to the absence of verifiable, machine-readable performance data.

The proposed framework aligns structural documentation with the physical hierarchy of modular construction (Fig. 1). By shifting verification from the global assembly to the component level, the workflow decouples a module's structural capacity from its specific project context. This hierarchical approach employs substructure analysis and a code-compliant capacity envelope calculation method. The result is a pre-certified structural unit that carries its performance data as an intrinsic attribute, ensuring seamless integration into diverse architectural designs across multiple lifecycles.

Using substructuring enables the analysis of modular systems in a hierarchical manner, where modelling and the analysis components as discrete subassemblies are straightforward and efficient [4, 5]. Each component type is initially modelled in high fidelity

to provide detailed insight into the stresses. Next, a reduced-order model is extracted by static condensation, keeping selected degrees of freedom to allow coupling to other parts. In this process, it is to be ensured that the reduced stiffness matrix is representative of the macro-level response of the module, contributing to the stiffness of a structure at the global level. Also, the coupling approach and the attachment nodes must be selected such that the internal forces in the component itself will be correctly determined in a back-calculation process at the component level, following a global static analysis of the entire building.

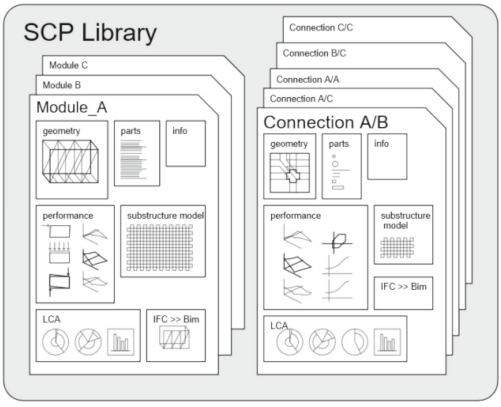


Fig. 2. Conceptual diagram of a structural component passport library.

To maintain compliance with the applicable structural code, we introduce a code-compliant capacity envelope (CCCE) calculation method applicable for spatial or planar subassemblies. The method maps the structural resistance of a component into a multi-dimensional load space [6]. This approach allows the definition of a capacity domain, calculated in accordance with the latest building standards. Therefore, load combinations within the capacity envelope are inherently code-compliant, enabling instantaneous verification of a module's resistance without repeated, project-specific calculations.

Lastly, the SCP documents the module's structural and environmental identity. It stores the condensed stiffness matrix and the code-compliant capacity envelope with essential metadata, including 3D geometry, material specifications, and embodied carbon indicators (Fig. 2). By providing a persistent digital record of structural performance, the SCP ensures that the module remains a verifiable asset throughout its service life and into secondary life cycles.

Building-level documentation follows a component verification protocol. The load distribution and reaction forces are backcalculated from the global static analysis of the building via substructure analysis. The reactions at the interface nodes are then checked against the components' capacity envelope to ensure code compliance.

3 Methodology

We implemented the proposed hierarchical documentation workflow on a single-bay portal frame modelled and partitioned into components to represent a simplified modular structure (Fig. 3). It features a 10-m span and 4-m eave height, utilising glue-laminated timber members (GL30h), with moment-resistant slotted-in steel plate doweled connections and fixed supports, subjected to a horizontal point load. This portal frame is divided into components to illustrate a modular structure. The frame is partitioned into three components by cuts at the connecting steel plate mid. This results in two structural component types: A (column), and B (beam), each including the respective part of the dowelled steel plate connection. The first step in the module's structural documentation is generating the substructure model.

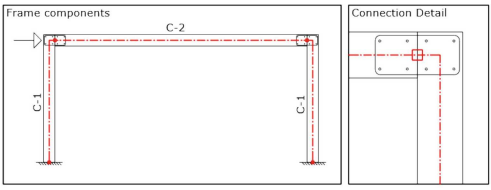


Fig. 3. Shematic design of the structure, components and the connection detail. The attachment nodes are shown with square rectangles.

The components are modelled at high fidelity using solid finite elements. The dowel connections are defined using surface-to-surface penalty-based contacts. The beams are defined with orthotropic linear elastic material behaviour [7, 8]. The finite element analyses were performed in Simulia Abaqus 2025, with Python 3.0 scripting used to automate the generation of geometry, material properties, assembly, boundary conditions, and substructure generation, as well as the global modelling approach. Each substructure is condensed to a few attachment nodes coupled to representative boundary regions of the components via kinematic coupling.

In parallel, to define the limit states of the components, the capacity was calculated as a function of the load space in accordance with EN 1995.1. Section 3, Section 8. Component load space axes are axial load, bending moments, and shear at end nodes. Finally, the SCP is generated by encoding the substructure model, the capacity envelope, and the additional metadata including EPD (Fig. 4).

Once the components' structural documentation is prepared, we proceed with the building-level documentation. A global structure is assembled using the component substructure models, tied together via interface nodes. Based on the reaction forces from the substructure analysis, the components are then checked against their respective CCCE.

The framework's accuracy and efficiency are assessed by comparing it with the typical project-specific linear workflow in accordance with EN 1995-1-1 standards, to a monolithic FEA model. The benchmarking aims to verify that the productised performance data in the SCP remains as reliable as traditional, project-bound engineering reports and that the numerical results are valid.

4 Results and Analysis

The numerical results confirm that the hierarchical documentation framework method maintains sufficient precision. The results show sufficient correlation with the benchmark calculations (Table 1). Differences in global results, such as reaction forces and sway, are negligible. At the component level, general stress values in members match results yielded from internal forces. However, higher values are experienced in stresses parallel to the grain. This is due to a more precise definition of the parts and their connection interactions, which captures stress concentrations at the slots' inner corners and effects of force redistribution and eccentricities in the connections on stress distribution (Fig. 5c, d).

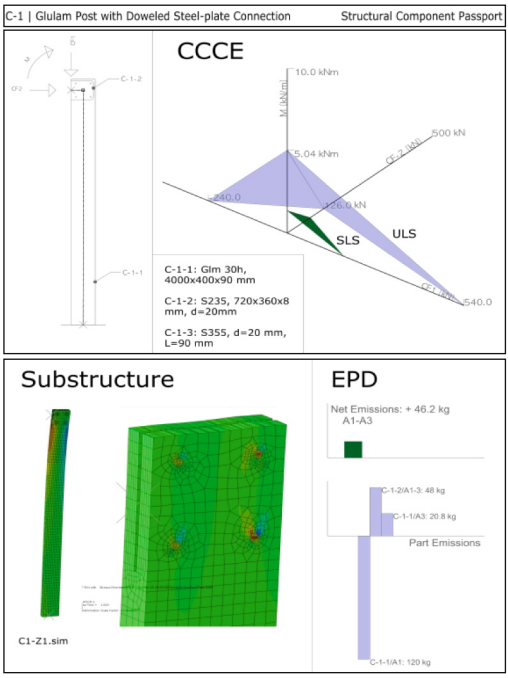


Fig. 4. Structural Components Passport of C-1, including design data, code-compliant capacity envelope, substructure model, and environmental product declaration.

Compared to the monolithic finite element analysis and the substructure analysis, slight deviations can be observed due to component partitioning. Changes in stress distribution can be experienced in the divided steel-plate parts of two adjacent components (Fig. 5a), compared to intact steel-plate parts in the full model (Fig. 5b).

The gains in engineering effort of the hierarchical documentation approach are clear. While the initial effort to prepare the component documentation is higher, building-level documentation becomes more straightforward and quicker. This is thanks to simpler computational modelling of the global model, reduced computation time, and decreased documentation effort.

Table 1. Comparison of the substructure analysis results with the baseline calculations.

	Sway	C-1: S11max	C-1: S11min	C-2: S11max	C-2: S11min	RF-x	RF-z	RM-y
	mm	MPa	MPa	MPa	MPa	kN	kN	kNm
Substructuring	11.3	5.3	−5.68	8.47	−7.93	1.23	5.48	10.84
Baseline	12.2	3.67	−4.02	7.92	−7.82	1.22	5.21	10.62

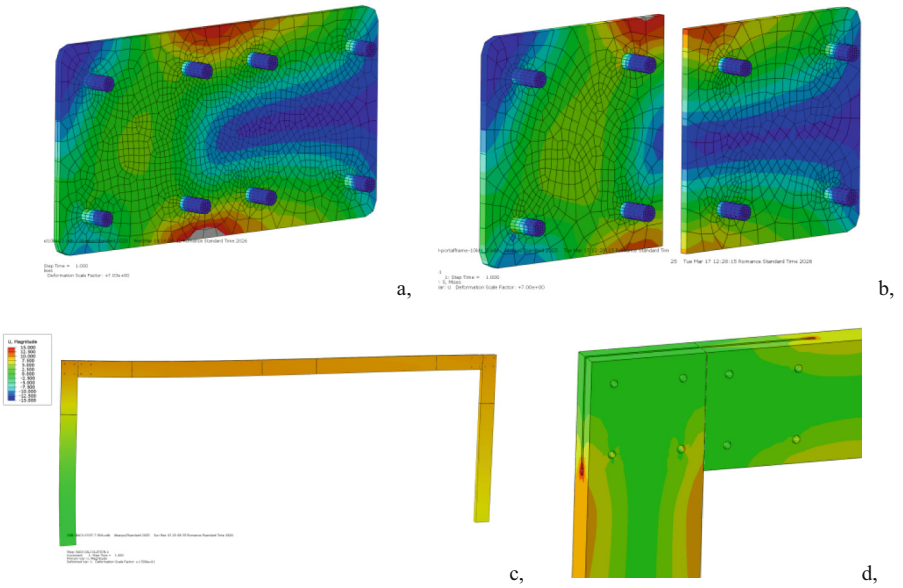


Fig. 5. Mises stress distribution in monolith FE model (a) and of the substructures (b); Displacement of the global structure (c) and extreme stresses at the connection details (d).

5 Discussion

The results demonstrate that hierarchical structural documentation can accurately represent modular structural systems while enabling a simpler and more effective engineering workflow. The combination of reduced-order modelling with capacity envelopes allows the structural behaviour of a module to be described by a concise mechanical summary and a defined performance boundary. This approach partially decouples structural verification from specific building configurations, allowing component-level performance data to be reused across multiple assemblies.

The proposed framework shifts structural verification from repetitive, project-specific analyses to a product-oriented approach in which the structural capacity of

a module is defined once and documented at the component level. Predefined performance boundaries enable modules to be incorporated into multiple structural configurations without necessitating repeated verification, consequently reducing engineering effort and shortening design-to-fabrication workflows. This approach aligns structural engineering with the principles of industrialised construction, as clearly defined product performance requirements allow manufacturers to adjust production parameters, support the use of local or secondary materials and encourage modularisation within the construction supply chain.

The SCP provides a mechanism for preserving structural knowledge over the lifecycle of building components. By storing structural performance data alongside geometric and lifecycle information, it creates a persistent digital record associated with the physical module. This supports later transformation, reuse, and relocation, addressing the loss of structural performance information over time as a key barrier to circular construction [9].

The illustrative case was primarily used to present the SCP and CCCE concepts, rather than to fully validate the method under realistic structural conditions. Further studies are therefore needed for panel-based and volumetric modular systems, including inter-module connections. The simplified case also limits discussion of scalability challenges, such as defining multi-dimensional capacity envelopes for complex components, implementing the framework in system-level analyses, and linking structural data with BIM and LCA workflows through standardised data protocols.

Future work should further investigate the incorporation of nonlinear behaviour and the integration of additional performance domains, such as vibration and building physics. Minor deviations observed in the component-level results, primarily due to partitioning choices and interface coupling, indicate that more complex connection geometries may lead to larger discrepancies, highlighting the need to further develop robust component partitioning strategies and assess their influence on accuracy.

6 Conclusion

This paper presents a hierarchical structural documentation framework for modular timber construction that shifts structural verification from project-specific building assemblies to reusable component-level performance data. The framework addresses a key barrier to circular construction: the loss of structural component information over a building's service life. The workflow combines substructure analysis with code-compliant capacity envelope calculations within a structural component passport (SCP). This enables product-oriented verification, where modules carry their own structural information throughout their lifecycle.

The framework links structural analysis to component documentation, supporting reuse and reconfiguration of timber modules in future buildings. The SCP provides a practical basis for component-based structural verification and supports the safe reuse of structural elements across projects.

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Circular Economy Gaps in Environmental Certifications: A Comparative Study of LEED and Selo Casa Azul

João Vitor Battaglin Loureiro(✉), Sérgio Fernando Tavares, and Maria do Carmo Duarte Freitas

Universidade Federal do Paraná, Curitiba, PR, Brazil
joao.battaglin@gmail.com

Abstract. The adoption of circular economy principles in the construction sector has increased the potential of environmental certification systems to promote resource efficiency, waste reduction, and lower life-cycle impacts. This study evaluates how circular economy strategies are incorporated into environmental certification systems by analyzing the latest versions of LEED and Selo Casa Azul + CAIXA. The research combines a literature review with a structured content analysis of certification criteria to assess the alignment with circular strategies, including reuse, recycling, durability, life-cycle extension, and embodied carbon assessment. The results show that LEED exhibits a higher level of integration of circular principles, especially through life-cycle assessment, material transparency, and embodied carbon considerations, although it still faces limitations regarding material reuse and design for disassembly. Conversely, Selo Casa Azul mainly incorporates circular aspects through efficiency-focused criteria, with limited emphasis on closed-loop material strategies. The study concludes that there is an uneven integration of circularity and identifies critical gaps in both systems, such as the reuse of materials and design for disassembly.

Keywords: Circular economy · Environmental certification · LEED · Selo Casa Azul · Resource efficiency

1 Introduction

The construction industry plays a key role in global environmental impacts due to its heavy use of natural resources and the significant production of construction and demolition waste, which accounts for about 30–40% of worldwide solid waste and includes large amounts of recoverable materials [11–17]. These effects have raised concerns about resource depletion, waste management, and greenhouse gas emissions throughout the building's lifecycle. In response, environmental certification systems have become important tools for encouraging more sustainable building practices by incorporating environmental objectives into measurable criteria [4].

Meanwhile, the circular economy (CE) paradigm has gained importance as a systemic approach that aims to separate economic growth from resource depletion. Circular

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strategies focus on reducing material use, reusing, recycling, increasing durability, and extending product life cycles, moving away from traditional linear "take–make–dispose" models toward closed material loops and regenerative systems [6–12]. In the built environment, circular economy principles offer a comprehensive framework for managing material flows across all life-cycle stages, from design and construction to operation and end-of-life management [18].

Integrating circular economy principles into environmental certification systems remains uneven. Most certifications still prioritize operational performance, such as energy and water efficiency, while giving limited attention to material flows, adaptability, and life-cycle recovery. This creates a mismatch: certification systems could support circular strategies but often lack clear mechanisms for reuse, design for disassembly, and material traceability [1–18].

This study addresses this gap by critically examining how circular economy principles are incorporated into environmental certification systems, focusing on the latest versions of LEED (Leadership in Energy and Environmental Design) and Selo Casa Azul + CAIXA. LEED is a globally recognized certification framework that increasingly emphasizes life-cycle impacts and embodied carbon. At the same time, Selo Casa Azul represents Brazil's national approach to sustainability in residential construction, particularly within social housing programs. By comparing these systems, the study aims to identify strengths, limitations, and opportunities to align circular economy strategies with certification standards better.

To achieve this, the research combines a literature review with a structured content analysis of certification criteria. As a contribution, the study proposes a framework structured around four dimensions to bridge the gap between current building standards and the Circular Economy (CE) paradigm. This framework shifts the focus from mere operational performance toward regenerative, closed-loop construction practices. The four dimensions are:

1. Design for Circularity: Integrating durability, adaptability, and Design for Deconstruction (DfD) to prevent premature obsolescence and facilitate resource recovery.
2. Material Cycles: Moving beyond basic recycling toward high-value component reuse and material traceability (e.g., through Material Passports) to manage resources across multiple life cycles.
3. Life Cycle Impacts: Establishing Life Cycle Assessment (LCA) and embodied carbon accounting as baseline criteria, ensuring a holistic view of environmental performance.
4. Incentives and Governance: Utilizing certification as a governance tool to create market incentives for circular business models, such as product-as-a- service and urban mining.

2 Circular Economy and Construction

2.1 Principles of the Circular Economy

The circular economy is based on strategies designed to preserve the value of products, materials, and resources for as long as possible while reducing waste. Key approaches include reducing material use, reuse, high-quality recycling, and design strategies that

improve durability, adaptability, and lifespan extension. Unlike traditional linear "take–make–dispose" models, circular systems focus on closed material loops and regenerative thinking, aiming to eliminate waste and pollution during the design phase and keep materials at their highest value across multiple use cycles [8–10].

2.2 Circularity in Construction

In the construction industry, circularity can be applied at various stages, from early design and material choice to construction, building operation, and end-of-life management. Important strategies include modular design, using recycled and reused materials, designing for disassembly, and maintaining material traceability throughout the entire lifecycle [3].

Despite increasing interest from academia and industry, the practical use of circular strategies remains limited. Barriers are typically categorized as technical (e.g., lack of standardized design for disassembly), economic (e.g., higher initial costs), and institutional or regulatory (e.g., fragmented supply chains and limited policy support) [7]. These obstacles hinder the widespread adoption of circular principles in everyday construction practices [12].

Environmental certification systems can assist in addressing these challenges by transforming abstract circular economy concepts into clear, measurable performance standards. However, the effectiveness of current certification schemes in implementing circular strategies varies significantly, revealing inconsistencies in how they manage material flows, adaptability, and long-term value retention within their assessment frameworks [2–13].

3 Environmental Certification Systems: LEED and Selo Casa Azul

3.1 Overview of LEED

LEED is one of the most widely adopted international environmental certification systems, organized into thematic categories such as Materials and Resources, Energy and Atmosphere, and Indoor Environmental Quality. Its recent versions explicitly align with circular economy principles by rethinking how materials are selected, used, and recovered throughout a building's life cycle. LEED v5 enhances its focus on near-zero carbon, resource responsibility, and resilience, broadening the system's scope to address whole-life environmental performance [21] better.

But, in fact, LEED v4.1 already advanced circularity by promoting durable design, maintenance, repair, reuse, remanufacturing, and closed-loop recycling, shifting the built environment away from the traditional linear "take–make–dispose" model. Through its Materials and Resources category, LEED encourages whole-building life- cycle assessment, responsible sourcing, reduction of construction and demolition waste, and material ingredient transparency—mechanisms that help keep materials in circulation at their highest value for as long as possible [20].

3.2 Overview of Selo Casa Azul

Selo Casa Azul is a Brazilian sustainability certification created by Caixa Econômica Federal to encourage improved environmental, social, and economic performance in residential buildings, especially within social housing programs. The system assesses projects across various aspects—including urban quality, architectural design, energy efficiency, water management, and responsible material use—using a structured set of socio-environmental indicators [5]. After 10 years of use, the certification needed updated guidelines to comply with new regulations, include recent innovations in the construction sector, and address changing urban and social conditions. The update aimed to make sustainable construction more appealing to developers and motivate projects with stronger environmental commitments. This led to the launch of the second phase of Selo Casa Azul + CAIXA in 2020, introducing a renewed framework better aligned with modern sustainability challenges [6].

Current versions of Selo Casa Azul emphasize efficient resource use and reduced environmental impact. Still, the integration of circular strategies—such as material reuse, design for disassembly, and closed-loop material flows—remains limited within its guidelines. This gap presents an opportunity to strengthen circularity-focused criteria and better support Brazil's shift toward regenerative construction practices.

4 Methodology

This study uses a qualitative research design that combines a literature review with a content analysis of environmental certification systems. The research was carried out to identify circular economy strategies relevant to the construction industry, based on peer-reviewed journal articles, conference proceedings, and institutional publications. Previous research consistently highlights strategies such as reuse, recycling, durability, design for adaptability, life-cycle extension, and embodied carbon reduction as key elements of circularity in the built environment [9–16]. Based on these findings, a unified set of circular strategies was developed to serve as the analytical framework.

Subsequently, the most recent versions of LEED and Selo Casa Azul were examined through structured content analysis. Certification credits, prerequisites, and performance requirements were systematically reviewed and mapped against the circular strategies identified in the literature review. This mapping enabled an assessment of the degree of alignment between each certification system and key circular economy principles, highlighting convergences, gaps, and opportunities for further integration [19].

5 Results

5.1 Integration of Circular Strategies in LEED

The analysis indicates that LEED shows a progressively stronger alignment with circular economy principles, especially in its most recent update, LEED v5. The system places increasing emphasis on whole-life carbon assessment, material circularity, and supply-chain transparency, reflecting a broader shift in global sustainability standards.

LEED v5 advances circularity by requiring project teams to evaluate embodied and operational carbon across the full building life cycle, positioning life cycle assessment (LCA) as a baseline expectation for certification. Credits related to material transparency, such as Environmental Product Declarations (EPDs), and incentives for low-carbon procurement further reinforce material awareness and responsible sourcing. Despite these advances, gaps remain, particularly regarding incentives for material reuse, design for disassembly, and multi-cycle material traceability. While LEED v5 introduces stronger requirements for carbon-aware material selection, it still offers limited mechanisms to ensure that materials can be recovered and reintegrated into future value cycles—an essential dimension of circularity.

By embedding these evolving requirements into a globally recognized certification framework, LEED serves as a practical driver of the adoption of the circular economy in the construction sector. Its structured credit system translates systemic circularity principles—such as resource loops, long-term value retention, and reduced material extraction—into measurable, project-level actions that can be implemented across diverse building contexts.

5.2 Integration of Circular Strategies in Selo Casa Azul

The analysis shows that Selo Casa Azul + CAIXA, the latest version, incorporates sustainability criteria that partially intersect with circular economy principles, though in a more limited and less explicit manner than international systems. The certification emphasizes responsible material use, water efficiency, urban integration, and social value, reflecting priorities specific to the Brazilian housing context [6]. Some criteria indirectly support circularity—such as waste reduction during construction, durability-oriented design choices, and incentives for efficient resource management. However, strategies central to circular economy frameworks, including material reuse, design for disassembly, and multi-cycle material traceability, remain underdeveloped or absent. The update expanded the system's scope to incorporate new regulatory and technological advances, yet its operationalization of circularity continues to prioritize efficiency over closing material loops. As a result, Selo Casa Azul contributes to sustainability in housing but still offers limited mechanisms for enabling circular material flows across the building life cycle.

6 Discussion

A cross-analysis of both certification systems uncovers different levels of alignment with circular economy strategies. LEED shows a more advanced and clear integration of circularity, especially through credits related to life cycle assessment, embodied carbon reduction, material transparency, and product disclosure. These aspects directly align with circular strategies found in the literature, allowing LEED to implement concepts such as long-term value retention and reduced material extraction. Although gaps remain—particularly in reuse and design for disassembly—LEED offers a structured way to bring circular practices into mainstream building projects.

In contrast, Selo Casa Azul adopts a broader sustainability framework but is less focused on circular material flows. Its criteria prioritize efficiency, social value, and responsible resource use but provide fewer incentives for strategies such as reuse, adaptability, or closed-loop material cycles. This difference reflects contextual priorities: while LEED responds to global decarbonization and transparency efforts, Selo Casa Azul tackles national housing challenges, affordability, and regulatory constraints. As a result, LEED more closely aligns with circular economy principles, while Selo Casa Azul offers opportunities for future improvement, especially in incorporating material circularity and lifecycle thinking into its criteria.

6.1 Expanding the Contribution: The Four Dimensions of Alignment

The comparative analysis reveals that while certification systems have evolved, they still lack explicit pathways for closing material loops. The framework proposed in this study addresses these gaps through four strategic dimensions:

Dimension 1: Design for Circularity. Current systems often prioritize the operational stage, yet circularity requires buildings to be designed as independent layers. By rewarding Design for Deconstruction (DfD) and adaptability, certifications can ensure that components are easily maintained or replaced without entire structure demolition, addressing the limitation found in both LEED and Selo Casa Azul regarding multi- cycle reuse.

Dimension 2: Material Cycles. A critical gap is the lack of material traceability. This study suggests integrating Material Passports into the criteria to verify the quality and history of secondary materials, thereby building market trust and facilitating reverse logistics.

Dimension 3: Life Cycle Impacts. The study demonstrates that embodied carbon is frequently overshadowed by energy efficiency. The proposed framework advocates for whole-building LCA as a mandatory pillar, allowing for a fair comparison between carbon-intensive monolithic structures and low-impact, flexible, demountable designs. Dimension 4: Incentives and Governance. To overcome economic barriers, certifications must act as systemic enablers. This dimension proposes specific weighting systems that favor ‘circular premiums’—awarding extra points for the use of materials from urban mines or the adoption of circular business models that redefine product ownership.

7 Conclusions

The study used a qualitative research approach that combined a literature review with content analysis of certification systems to evaluate how circular economy principles are integrated into building sustainability. The research helped identify key circular strategies relevant to the construction industry—such as reuse, recycling, durability, adaptability, life-cycle extension, and embodied carbon reduction—which were then combined into an analytical framework to assess certification criteria.

Applying this framework to the latest versions of LEED and Selo Casa Azul revealed clear levels of alignment with circularity. LEED shows increasingly strong integration

of circular economy principles, especially through credits focused on life cycle assessment, material transparency, and embodied carbon reduction. These elements indicate a shift toward whole-life performance and supply-chain accountability, turning systemic circularity ideas into measurable project actions. However, gaps still exist in areas like material reuse, design for disassembly, and multi-cycle material traceability, which are crucial for closing material loops.

The Selo Casa Azul, in contrast, incorporates sustainability criteria that intersect with circularity mainly through efficiency-focused strategies such as waste reduction, durability, and responsible material use. The update broadened its scope to reflect new regulatory and technological contexts, but the certification still offers limited mechanisms for enabling circular material flows. Its focus remains on social housing priorities, resource efficiency, and contextualized sustainability outcomes rather than on explicit circular-economy pathways.

The comparative analysis shows that LEED aligns more fully with circular strategies identified in the literature. In contrast, Selo Casa Azul offers opportunities for future improvement, especially in incorporating life-cycle thinking, material recovery, and design for adaptability. These findings highlight the need for certification systems to go beyond efficiency-based approaches and adopt strategies that support regenerative, closed-loop construction practices.

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Think Inside the Box: A Circular Construction System

Stavroula Leoudi(✉), Emmanouela Myrtaki, Laura Fokkelman, and Casey Poot

Faculty of Architecture and the Built Environment, Delft University of Technology, Delft 2628 BZ, The Netherlands
celialeoudi@gmail.com

Abstract. Think-Inside-the-Box is a modular, box-in-box construction system incorporating reversible design, dry connections and the integration of bio-based and waste-derived materials. The project develops a construction logic where each timber frame functions simultaneously as a transport container and a building element. All components required for one structural grid are delivered in 3.7 m^3 kit −1.4 t- which unfolds on site into structure, insulation and cladding. This consolidation reduces packaging waste and delivery trips by ~80%, enabling up to 17 kits per standard truck (6 × 10 m building unit = 12 kits). Materials are merged into a single truckload, replacing ~6 conventional deliveries and reducing transport-related emissions by ~60% (freight factor: 139 g CO_2e/t-km). The system combines reclaimed laminated timber frames with CNC-cut OSB puzzle panels and mycelium insulation blocks, supplemented by reused egg cartons enclosing cotton for enhanced acoustic performance. Heat-pressed mycelium and spent coffee-ground composite tiles are used for finishing. Bio-grown mycelium offers CO_2-negative potential, fire resistance and low thermal conductivity (~0.05 W/mK), while coffee composites valorise a waste stream at optimal stability. Assembly relies on interlocking joints and wedges, facilitating full disassembly. Material and process development (mould and recipes) and a full-scale mock-up validated assembly logic and revealed tolerance and mould-performance limits, informing revisions. The system targets scalable single-storey buildings, demonstrated via a 60 m^2 office case study. Regulatory feasibility requires further testing for fire, structural performance and weathering. By integrating all building elements into a kit-of-parts, Think-Inside-the-Box transcends material substitution to achieve system-level reuse, simultaneously reducing waste, transport impacts and assembly complexity.

Keywords: Circular Building · Bio-based Materials · Reclaimed Wood · Mycelium · Food Waste

1 Introduction

The construction sector faces a dual challenge: reducing embodied environmental impacts and minimising End-of-Life (EoL) waste. This challenge is increasingly addressed through circular economy policies aimed at reducing virgin material consumption and waste generation. In the Netherlands, this agenda is articulated in *A Circular*

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Economy in the Netherlands by 2050 [1], while at the EU level the *European Green Deal* identifies circularity as central to achieving climate neutrality by 2050 [2]. EU waste policy further supports this transition by setting re-use and recycling targets, including 65% municipal waste recycling by 2035 [3]. Together, these frameworks position circular material use, design for reversibility and waste prevention as key strategies for the built environment. Modular and prefabricated construction offer significant potential to improve material efficiency, reduce waste and shorten construction time. Advances in digital design and CNC-based fabrication enable the precise manufacture of components and interlocking geometries for dry assembly [4]. In parallel, circular construction increasingly integrates reclaimed, bio-based and waste-derived materials, including reclaimed timber, mycelium-based composites (MBCs) for insulation and spent coffee grounds (SCG) as a valorised food-waste resource for building applications [5, 6].

Despite these advances, circularity in modular construction is still constrained by irreversible joints, complex assemblies, extensive packaging and fragmented logistics, which limit disassembly, recovery and transport efficiency. In response, the Think-Inside-the-Box concept proposes a circular box-in-box construction approach that integrates dry connections, reclaimed timber, bio-based and waste-derived materials within a transport-efficient kit-of-parts. Each building element functions both as a transport container and a permanent architectural component, embedding the shipping box within the building system and reducing construction waste. Based on a demountable timber frame, CNC-cut puzzle panels, modular insulation units and cladding, the approach enables efficient on-site assembly, disassembly and reconfiguration. The paper's main contribution is a logistics consolidation strategy linking reversible timber framing with experimental material streams: MBCs for insulation and interior tiles and SCG composites for exterior finishes. A design methodology is demonstrated through a scalable single-storey office case study and evaluated initial thermal and transport performance, assembly processes and material behaviour via a full-scale prototype.

2 Methodology

2.1 Design Approach

Criteria. The system is structured around four interrelated criteria, each associated with measurable performance indicators. *Logistics consolidation* serves as the primary design driver, reducing multiple shipments to one combined delivery to minimise transport and packaging waste. *Reversibility* is defined as a dry, mechanical assembly using wedges and interlocking joints, wherever feasible. *Standardisation* is achieved by repeated grid kits, supporting interchangeability and scalable layouts. *Material circularity* prioritises reclaimed timber for the primary structure and incorporates bio-based and waste-derived materials in replaceable subcomponents.

Waste Streams and Bio-Based Materials. Waste streams vary across sectors creating opportunities for integration into closed-loop material systems. The agri-food sector is promising because its by-products are bio-based, generated consistently and, depending on processing, can remain compatible with organic EoL routes such as biodegradation.

Upcycling low-value residues into high-performance applications can extend material service life and improve overall resource efficiency.

MBCs provide a sustainable alternative to conventional fossil-based insulation materials such as polyurethane and polystyrene [9]. These composites are produced by inoculating agricultural by-products such as hemp, flax and straw, typically with white-rot fungi. This low-energy bio fabrication process forms lightweight, biodegradable materials, offering high fire performance, depending on formulation [7]. MBCs typically exhibit densities of 60–180 kg/m^3 and thermal conductivities of 0.04–0.06 W/mK, making them suitable for insulation. The mechanical performance of MBCs is strongly influenced by substrate processing, with fibre size compaction generally leading to higher density and improved mechanical strength [9]. Prospective life cycle assessment (LCA) studies typically assume a 30-year reference service life for mycelium insulation, rather than reporting an empirically validated lifespan for these composites. EoL scenarios include sequential reuse and potential reintegration as substrate in new composite production [8].

SCG, the solid residue of brewing, account for about 6×10^6 t annually worldwide [6]. Composed mainly of lignocellulosic matter with residual oils and proteins, SCG can be dried, milled and sieved into a filler for composites [9]. Mechanical performance depends on particle size and content: particles $\leq$125 μm and a filler loading of 45 wt% yielded the best strength and rigidity. Hot pressing (~150 °C, ~6 MPa, ~15 min) enables stable and repeatable panel production suitable for façade applications [9].

Geometric Analysis. The system is demonstrated through a single-storey 6 × 10 m office prototype, organised through the repetition of modular structural grids (0.80 × 6.00 m) (Fig. 1). The primary load-bearing structure consists of laminated OSB columns and beams (300 × 50 mm) assembled through a dry connection system and wedges. Precise fit and repeatability are achieved through CNC-cut interlocking geometries, which also support self-alignment during assembly. Lateral stability is supported by the shelf elements, which act as secondary structural diaphragms within each grid. Their wedged, interlocking connections provide in-plane stiffness, enabling shear redistribution through the shelf-column assembly. This connection logic is extended beyond the primary frame; the enclosure layers are likewise conceived as removable subcomponents, reinforcing reversibility at both structural and architectural scales. The building is supported by a gabion foundation (400 × 600 mm) filled with rubble, raising the floor ~580 mm above ground level to improve moisture protection while maintaining reversible interface with the ground.

As shown in Fig. 1, the façade and roof adopt a layered envelope strategy, incorporating 150 mm mycelium insulation blocks, followed by 20 mm CNC-cut OSB puzzle panels as the primary enclosure layer. The external finish is formed by 10 mm SCG composite tiles mounted on 20 × 50 mm timber battens, creating a ventilated and replaceable outer skin. The floor assembly combines structural timber framing with 70 mm mycelium insulation blocks and cotton-filled reused egg cartons as porous acoustic infill for vibrations, impact-sound and cavity-resonance control. The walking surface is formed by 12 mm heat-pressed mycelium tiles installed over 20 mm underlayment layers. To enable scalable production of the bio-based components, the mycelium elements are fabricated

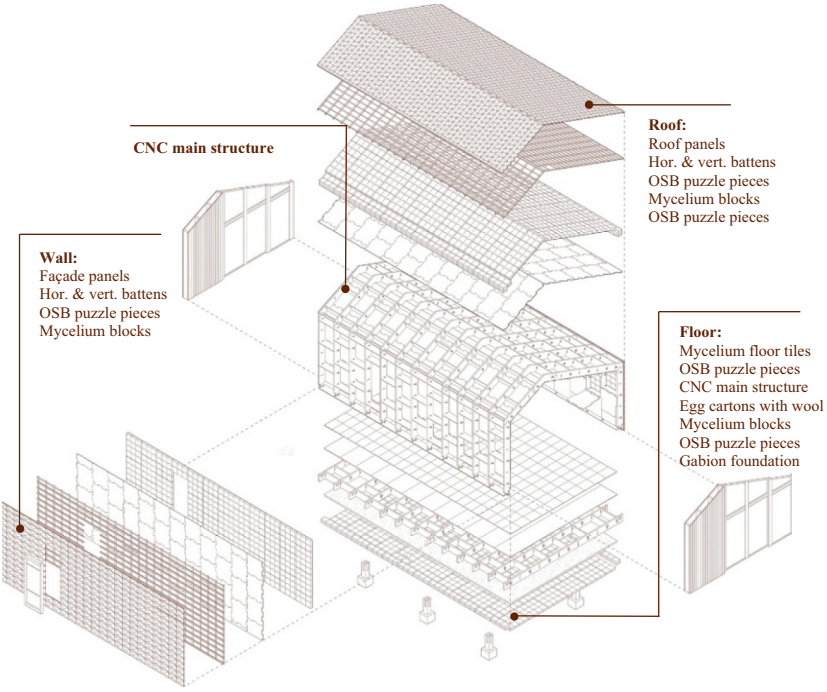


Fig. 1. Exploded axonometric analysis of the 60 m^2 building unit.

using three mould types: (i) heat-pressed floor tiles, (ii) floor insulation blocks and (iii) adjustable wall-block mould, generating a stacked interlocking geometry (Fig. 2).

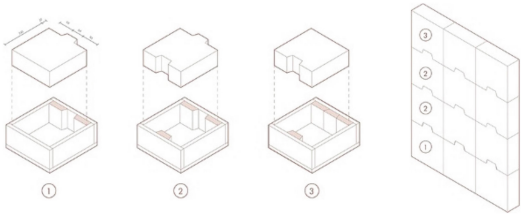


Fig. 2. Adjustable wall-block mould and configuration of mould elements.

Performance Analysis. The system applies circular design principles across materials, design and manufacturing, with logistics consolidation as the primary performance strategy. It was evaluated by comparing conventional multi-supplier delivery to a consolidated kit-of-parts system for a functionally equivalent 60 m^2 single-storey unit, defined by comparable floor area, structural stability and envelope thermal performance (targeted Rc $\approx$ 3.5–6.0 m^2K/W). In the baseline scenario, each material stream is assumed to travel 100 km/trip; transport work was calculated as Σ (mass $\times$ distance) and emissions

were derived using the STREAM (2020) factor (139 g CO_2e/t-km). Impacts from material production, construction equipment, operational energy, maintenance, replacement cycles and End-of-Life (EoL) processing are excluded. The kit-based model reduces deliveries by ~80%, transport emissions by ~60% and saves 0.512 t CO_2e per building unit (Table 1).

Table 1. Comparison table of transportation parameters.

Parameter	Conventional baseline	Kit-based model
Delivery structure	Six separate shipments due to supplier specialisation and material incompatibility	One consolidated truckload
Shipment breakdown	(i) Concrete & framing 24 t; (ii) Hardware 0.5 t; (iii) Cladding 18 t; (iv) Insulation 4 t	12 kits × 1.4 t each
Total transported mass	46.5 t	16.8 t
Total transport work	4650 t-km	1680 t-km
Transport emissions	0.646 t CO_2e	0.234 t CO_2e

Packaging is integrated into the structural container, eliminating supplier-specific pallets and protective wrapping and thus reducing packaging waste (Fig. 3).

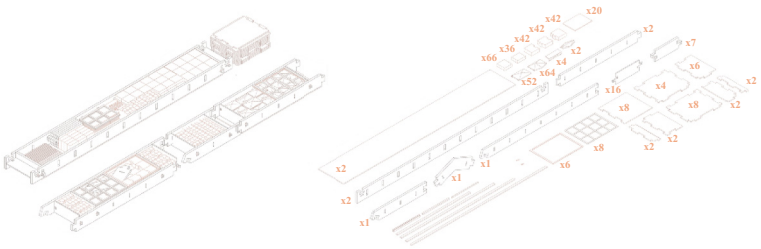


Fig. 3. One kit, where the building elements are designed to convert into a shipping box.

At the material level, thermal performance was evaluated through a steady-state 1D Rc calculation based on the wall build-up (ISO 6946 approach). Thermal conductivities (λ) were adopted from datasheets. The external cladding (coffee tiles, profiles, battens) was treated as a rainscreen zone and excluded from the insulating build-up, while the 210 mm void was modelled as an air cavity under two boundary conditions (airtight vs. intermittently open shelf use). The wall achieves an estimated Rc of ~3.5 m^2K/W, depending on the assumed λ values and cavity conditions.

2.2 Experimental Approach

A full-scale mock-up was fabricated to validate assembly tolerances and interface behaviour of the "box-in-box" kit-of-parts -primary frame, CNC puzzle panels, mycelium infill and pressed mycelium finishes- under dry-fit conditions (Fig. 4).



Fig. 4. (left) full-scale mock-up design; (right) pictures of realised mock-up.

Mycelium insulation blocks were produced using inoculum supplied by ECO Consult (Bleiswijk) and grown on wood shavings. Reusable styrofoam moulds were wrapped with plastic cling wrap and covered after filling to limit moisture loss and maintain a closed microclimate during incubation. Growth time in mould was 4 days, while post-growth deactivation was conducted in a domestic convection oven using an isothermal hold at 180 °C/60 min, followed by a staged cool-down to 160 °C and 140 °C with 20 min holds each. Mycelium floor tiles were manufactured via heat pressing, with a 600 × 600 mm press bed. Two mould frames were tested in plywood and OSB. A heat-resistant baking sheet was used as a release layer. Three heating cycles were tested at a nominal pressure of 0.5 bar with controlled temperature: 50 °C/5 min, 180 °C/35 min and 200 °C/35 min. The structural mock-up used reclaimed 18 mm wood panels laminated into members by bolting three layers to reach desired thickness; joints were marked and cut as a single member. The column-beam dowel geometry was cut manually to test fit sensitivity, while puzzle panels were CNC-milled to evaluate fit accuracy and assembly speed.

3 Results and Discussion

The full-scale mock-up highlighted main issues in hot pressing of mycelium, tolerance control in dry joints and façade substructure buildability. For the mycelium floor tiles, process stability depended on mould stiffness and thermal exposure. The plywood mould frame deformed under heat and it was replaced by an OSB mould. Heating cycle governed consolidation: 50 °C/5 min yielded insufficient bonding, 180 °C/35 min produced a structurally stable tile and 200 °C/35 min maintained stability but produced a darker surface, consistent with higher thermal exposure. For the primary structure, tolerance accumulation became evident at the dry joints. The manually cut column-beam dowel geometry introduced fit variability, demonstrating that demountable assembly requires either jig-guided machining or redesigned joints with explicit tolerance allowances. Cladding substructure exposed a detailing gap: the initial design did not provide a robust fastening zone between battens/rails and the supporting layer, leading to on-site modification of geometry and fixing logic to achieve practical installation (Fig. 5).



Fig. 5. (left) Process of mycelium tile development; (right) Redesign of batten substructure.

Overall, at the current stage, the timber frame, CNC-milled OSB panels and dry-fit assembly logic can be considered prototype-ready, whereas the mycelium insulation and tiles and SCG composite cladding remain experimental. Their circular applicability depends on achieving sufficient durability and service life without protective coatings or additives that compromise bio-based content or EoL pathways.

4 Conclusions

Think-Inside-the-Box presents a circular box-in-box construction system in which each structural module serves both as a transport container and as a building frame, enabling dry assembly. The system is characterised by rapid deployment, reconfiguration and transport consolidation, yet at the current stage of development, its implementation remains limited by the tolerance requirements of dry joints and the certification readiness of bio-composites. In the demonstrated logistics scenario, one single-storey 60 m^2 building unit is delivered as 12 kits in one trip, resulting in reduced packaging, approximately 80% fewer delivery trips and an estimated 60% reduction in transport-related emissions.

Feasibility was examined through a prototype-driven methodology combining material selection, digital fabrication and full-scale iteration. The full-scale mock-up integrated reclaimed timber, CNC-milled puzzle panels, mycelium insulation and heat-pressed floor tiles. SCGs were identified in the literature as a potentially suitable local waste-stream feedstock for cladding composites but were not experimentally implemented due to equipment limitations within the project timeframe. Prototype testing informed design revisions: tile consolidation was achieved at 0.5 bar, 200 °C/35 min; mould tooling was changed from plywood to OSB due to thermal deformation; manual cutting of the column-beam dowel joint resulted in tolerance drift, indicating the need for CNC machining and defined clearances; and the hanging interface was redesigned to provide a clearer fastening zone. The study therefore demonstrates the technical feasibility of a logistics-integrated modular kit-of-parts based on reclaimed timber, CNC-milled OSB panels and MBCs.

Future work should focus on generating certification and benchmark-ready evidence through expanded performance testing and regulatory alignment, including reaction-to-fire classification (EN 13501-1), durability and moisture testing and structural compliance of timber elements and connections. Circularity should be assessed under ISO 20887, while environmental evaluation should be extended from transport logistics to a whole-system LCA, including virgin material production and transportation, durability, maintenance, replacement cycles and EoL scenarios.

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Selective Deconstruction Versus Business-as-Usual Demolition: An LCA-Based Assessment of CDW Management Scenarios

Jan Pešta(✉), Barbora Vlasatá, and Tereza Pavlů

Czech Technical University in Prague - University Centre for Energy Efficient Buildings, Třinecká 1024, 273 43 Bustěhrad, Czech Republic
jan.pesta@cvut.cz

Abstract. Pre-demolition audits represent a key instrument for enabling selective deconstruction and improving the environmental performance of construction and demolition waste (CDW) management. This paper presents a life cycle assessment (LCA)–based case study in which a pre-demolition audit and the subsequent real deconstruction of a administrative building were used to systematically map and evaluate alternative CDW management scenarios. The study compares a real deconstruction scenario, implemented on the basis of a detailed pre-demolition audit, with a conventional business-as-usual (BAU) scenario reflecting standard demolition and waste treatment practices. The system boundary covers demolition-related life cycle modules C2–C4 and benefits beyond the system boundary (module D), including transport, processing, disposal, and recycling benefits, in accordance with EN 15804 + A2. Modelling was performed in SimaPro software using the ecoinvent 3.7 database. The results show that the real scenario based on selective deconstruction achieved substantially higher environmental benefits than the BAU scenario. Overall, the selective approach resulted in a net saving of 872 t CO_2 equivalent, corresponding to approximately 15% higher climate benefits compared to conventional demolition practices. Transport impacts were found to be relatively low, while the most significant environmental benefits originated from recycling of aluminium, steel, and glass. Concrete recycling also contributed to climate benefits, particularly when highquality recycling routes were applied. The case study demonstrates how predemolition audits can serve as a robust data source for scenario-based LCA of CDW management and for identifying environmentally preferable waste treatment pathways.

Keywords: LCA · CDW · waste management · predemolition audit · selective deconstruction

1 Introduction

The construction sector is a major contributor to resource consumption, greenhouse gas emissions, and waste generation. Construction and demolition waste (CDW) accounts for approximately 25–30% of total waste in the European Union, making its effective management essential for achieving circular economy objectives [1].

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Selective deconstruction has emerged as a key strategy to improve CDW management by enabling better separation of materials and increasing recycling and reuse rates compared to conventional demolition [2]. An important supporting tool is the pre-demolition audit, which provides a structured inventory of materials and facilitates the identification of appropriate waste treatment pathways [3].

However, current predemolition auditing is focused on ambitions framed with recovery rates, which describe only impact on availability of materials and do not assess other environmental impacts.

Life cycle assessment (LCA) is widely used to evaluate environmental impacts of buildings, including end-of-life stages [4]. Previous studies have shown that improved CDW management can significantly reduce impacts, particularly global warming potential (GWP) [5]. However, results are often based on simplified assumptions, highlighting the need for studies using real project data [6].

This paper presents a case study of a residential building demolition where a pre-demolition audit informed selective deconstruction. An LCA-based approach is used to compare a real scenario with a conventional business-as-usual (BAU) scenario. The aim is to quantify environmental impacts and demonstrate the potential of selective deconstruction to improve CDW management and reduce environmental burdens.

2 Methodology

2.1 General Approach and LCA Framework

The methodological approach is based on linking quantified material flows with corresponding environmental datasets in order to calculate the resulting environmental impacts. The life cycle assessment (LCA) was performed in accordance with relevant standards for construction products and building assessment, particularly EN 15804 + A2, ensuring consistency in system boundaries, impact categories, and reporting structure. Material quantities were derived from project documentation provided by the client, with a key input being a detailed bill of materials delivered in a spreadsheet format. This inventory formed the basis for the life cycle inventory (LCI), where individual material flows were systematically matched with environmental datasets within the SimaPro software environment. The software integrates both specific Environmental Product Declaration (EPD) datasets and generic datasets, primarily from the ecoinvent database (version 3.7), enabling a consistent and transparent modelling approach.

The calculation principle consists of assigning each material flow to an appropriate dataset representing its treatment process (e.g., recycling, disposal) and associated transport. The resulting environmental impacts are then aggregated across all materials and processes to quantify the overall environmental performance of the assessed scenarios.

2.2 System Boundaries and Life Cycle Modules

The system boundaries of the study focus on end-of-life stages of the building, specifically modules C2–C4 and module D, in accordance with EN 15804 + A2. The following life cycle stages were included:

- C2 – Transport: transport of demolition materials from the site to processing or disposal facilities, including distances specific to each material stream,
- C3 – Waste processing: operations related to sorting, treatment, and recycling of materials,
- C4 – Disposal: final disposal processes such as landfilling or energy recovery,
- Module D – Benefits and loads beyond the system boundary: potential environmental benefits and impacts associated with material recovery, recycling, and substitution of primary materials.

Processes related to on-site activities, including dismantling, selective deconstruction, and handling at the demolition site (module C1), were excluded from the system boundary. This exclusion reflects the focus of the study on downstream waste management processes and ensures comparability between the assessed scenarios.

2.3 Life Cycle Inventory and Data Sources

The life cycle inventory (LCI) was based on a detailed overview of material flows obtained from the demolition project. The inventory data were provided by a designated contact person responsible for material flow documentation and were considered representative of the real deconstruction process.

Environmental datasets used in the modelling were sourced primarily from the ecoinvent 3.7 database. The selection of datasets followed a hierarchy prioritizing geographical and technological representativeness. Whenever possible, datasets reflecting Central European or specifically Czech market conditions were used.

2.4 Modelling of Recycling and Substitution Effects

Potential environmental benefits associated with material recovery were modelled using the substitution approach in module D. Recycled materials were assumed to substitute equivalent products made from primary raw materials, thereby avoiding the environmental impacts associated with primary production.

The modelling of substitution effects was material-specific and reflected realistic recycling pathways. High-value recycling (e.g., metals and glass) was assumed to result in substitution of primary materials with similar functional properties. In contrast, lower-quality recycling processes (downcycling), such as the use of recycled concrete for backfilling applications, were modelled with reduced substitution benefits, reflecting their limited ability to replace primary materials in high-performance applications.

2.5 Description of the Assessed System

The analysed system represents the actual management of materials and products resulting from the demolition of a residential building located in the Holešovice district (Prague). The system includes all processes related to the transport, treatment, recycling, and disposal of demolition waste, as well as the associated environmental benefits from material recovery.

2.6 Definition of Scenarios

Two scenarios were defined and compared:

- Real scenario (selective deconstruction): based on actual demolition practices informed by a pre-demolition audit, with an emphasis on material separation and high-quality recycling,
- Conventional scenario (business-as-usual, BAU): representing standard demolition and waste management practices, defined based on expert assumptions and common industry practice.

The key differences between the scenarios lie in the level of material separation and the resulting waste treatment pathways. In the conventional scenario, lower levels of sorting and recycling efficiency are assumed.

For example, in the case of concrete, the conventional scenario assumes its use as recycled aggregate primarily for backfilling applications. This represents a typical down-cycling pathway, where the material does not substitute natural aggregate in structural concrete. In contrast, the real scenario includes higher-quality recycling routes, enabling greater substitution of primary materials and thus higher environmental benefits.

The definition of the conventional scenario is based on the authors' experience and reflects typical practices observed in the construction and demolition sector. This approach allows for a meaningful comparison between current standard practices and improved waste management strategies enabled by pre-demolition audits.

3 Results and Discussion

3.1 Results by Demolition Phases

To evaluate the effectiveness of the applied selective deconstruction approach, a conventional (business-as-usual, BAU) scenario was developed as a benchmark representing typical material management practices. This scenario, defined based on expert assumptions and common industry practice, enables a direct comparison with the real deconstruction scenario derived from the pre-demolition audit.

When comparing the two scenarios using the global warming potential (GWP) indicator, the conventional scenario shows approximately 15% lower environmental benefits than the real scenario. In other words, the selective deconstruction approach achieves a significantly higher reduction in greenhouse gas emissions, confirming its environmental advantage over standard demolition practices.

For a more detailed interpretation of the results, the demolition process was divided into three phases:

- Demolition phase 1: removal of interior materials,
- Demolition phase 2: removal of structural components,
- Demolition phase 3: removal of exterior building elements.

The comparison of scenarios across these phases reveals that the most significant differences occur in demolition phase 1, which includes interior materials. This phase is particularly sensitive to the level of material separation and the choice of waste treatment pathways.

3.2 Interpretation of GWP Results

The aggregated GWP results by demolition phase (Fig. 1) illustrate the contribution of each phase to the overall environmental performance of both scenarios.

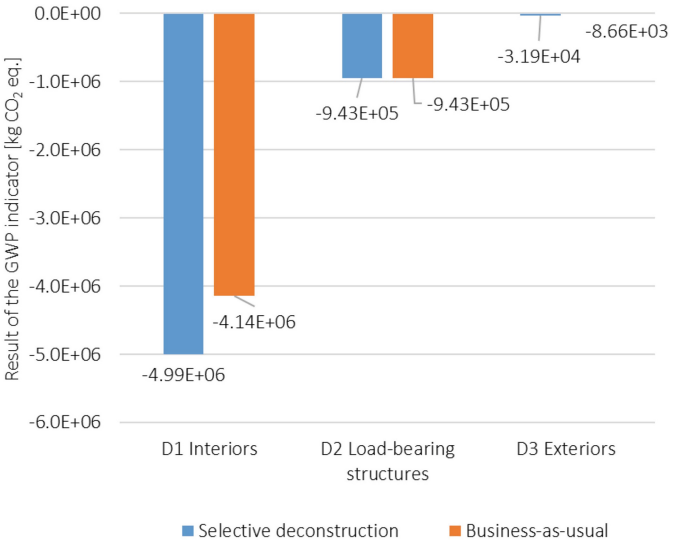


Fig. 1. The aggregated GWP results by demolition phase, comparing two scenarios.

The figure clearly shows that:

- demolition phase 1 is the main driver of differences between the scenarios,
- demolition phase 2 contributes substantially to total impacts due to the large volume of materials, but with relatively small differences between scenarios,
- demolition phase 3 plays a secondary but still relevant role.

Overall, the results confirm that selective deconstruction, supported by a pre-demolition audit, enables more efficient material recovery and leads to improved environmental outcomes, particularly in material streams where multiple treatment options exist.

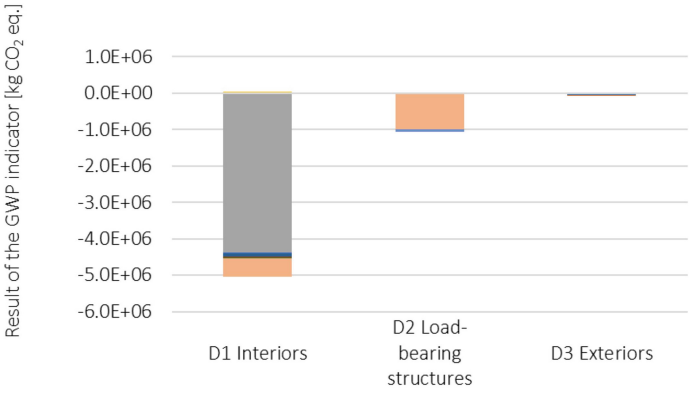
The findings also indicate that the greatest potential for improvement lies in optimizing the handling of interior materials and increasing the share of high-quality recycling and reuse pathways.

3.3 Results of Module D

Potential environmental benefits associated with recycling and reuse were modelled using a substitution approach, where secondary materials replace equivalent products made from primary raw resources. The results for individual material streams, disaggregated by demolition phases, are presented in Fig. 2.

The most significant environmental benefit was associated with aluminium recycling, modelled as a substitution of primary aluminium ingot production. This result is primarily driven by the high energy intensity and corresponding emissions of primary aluminium production processes. Consequently, even relatively small quantities of recovered aluminium lead to substantial avoided impacts in terms of GWP. It should be noted, however, that the choice of datasets and environmental data can strongly influence the overall results and conclusions of the study. In this case, datasets were selected with regard to geographical relevance and the comparability between the recycled material and the substituted product. A similar effect was observed for steel, which represents another major contributor to environmental benefits. Due to the high energy demand of primary steel production, recycling of steel elements from both interior components and structural systems results in considerable avoided emissions.

Further notable environmental benefits were identified for materials such as glass wool, flat glass, and gypsum-based products (e.g., plasterboard). Although their individual contributions are lower compared to metals, their cumulative effect is significant due



	D1 Interiors	D2 Load-bearing structures	D3 Exteriors
Bitumen			-5.3E+02
Clay			-3.9E+04
Concrete		-5.1E+04	-5.1E+03
Wood	1.8E+03		
Steel	-5.1E+05	-1.0E+06	
Plastic pipes	-1.4E+01		
Gypsumboard	-2.3E+04		
Gravel	-6.3E+02		
Mineral wool	-5.8E+02		
Glass wool	-1.4E+04		
Glass	-9.4E+04		
EPS	9.5E+03		
Electrowaste	-2.5E+04		
Aluminium	-4.4E+06		

Fig. 2. Potential benefits of material recovery calculated in module D, aggregated GWP results by demolition phase, real case scenario.

to their presence across multiple demolition phases. In addition, despite relatively small quantities, electrical and electronic waste (WEEE) showed a favourable environmental impact, highlighting the importance of proper collection and recycling of these material streams.

The results also indicate that not all material flows lead to positive outcomes in module D. In the case of expanded polystyrene (EPS), the benefits were modelled based on energy recovery. Although this process provides some substitution benefits through energy generation, the overall impact remains negative in terms of GWP due to emissions associated with incineration.

Overall, the results of module D confirm that the environmental performance of CDW management is strongly influenced by the quality of recycling pathways and the substitution potential of individual materials.

Although the study is based on a single case study, the results are considered relevant for a broader range of buildings where conventional demolition still dominates CDW management. Buildings with higher shares of metals or reusable components are likely to achieve even greater benefits from selective deconstruction, while mineral-based structures may show smaller relative improvements. An important advantage of selective deconstruction is also the prevention of material contamination during demolition. For example, cleaner separation of concrete fractions enables their use in higher-value recycling applications instead of low-grade backfilling, thereby increasing their substitution potential and associated environmental benefits.

4 Conclusion

The LCA study of the demolition of the administrative building demonstrated the significant role of selective deconstruction and environmentally responsible waste management in reducing the carbon footprint of demolition activities. The analysis confirmed that the real scenario, based on selective material separation, recycling, and reuse, achieves approximately 15% greater climate benefits (in terms of GWP reduction) compared to the conventional scenario, which assumes a higher share of landfilling and less efficient material recovery. The most substantial environmental benefits were associated with the recycling of materials with high embodied emissions, particularly aluminium, steel, and glass. In contrast, concrete, due to its large volume, was identified as a major contributor to total emissions, despite relatively similar treatment pathways in both scenarios. This highlights the importance of improving recycling quality and utilization pathways for mineral materials.

Overall, the findings confirm that environmentally conscious demolition practices can significantly improve the environmental performance of CDW management and support the transition towards more circular construction practices. Future research should focus on integrating module C1 impacts into comparative assessments, evaluating multiple building typologies and regional contexts, and improving the modelling of material quality and reuse potential. Further work is also needed to better connect pre-demolition audits with design-for-deconstruction strategies and digital material documentation approaches supporting circular construction.

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Comparative Environmental Assessment of Waste- and By-product-Based Compressed Earth Block Wall Systems

Adilson Paula Junior(✉), Cláudia Jacinto, Elisabete Teixeira, and Ricardo Mateus

ISISE, ARISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal
id8639@alunos.uminho.pt

Abstract. The environmental performance of masonry systems strongly influences the overall environmental impact of buildings. This study presents a comparative environmental assessment of wall systems built with compressed earth blocks (CEBs) incorporating industrial waste and by-products, alongside conventional masonry solutions. The analysis is based on life cycle assessment (LCA) using life cycle inventory data obtained from a Portuguese producer. The CEB solutions correspond to previously optimised formulations. These include blocks incorporating cork granules and waste tyre textile fibres (WTTF), as well as two types of construction and demolition waste (CDW): railway concrete and ceramic tile waste. The earthen solutions are compared with conventional masonry systems, namely fired ceramic bricks and concrete blocks. The functional unit adopted is 1 m^2 of interior partition wall. The assessment follows a cradle-to-gate perspective (modules A1–A3 of EN 15804:2012 + A2). It includes raw material supply, transport and block production. Environmental impacts were quantified through eight indicators, primarily the Global Warming Potential (GWP). Results show that all CEB wall solutions present lower environmental impacts than conventional masonry systems across all indicators. The GWP of the optimised CEB walls ranges from 16.9 to 21.5 kg CO_2 eq/m^2. This corresponds to reductions of 38–51% compared with ceramic hollow brick (34.4 kg CO_2 eq/m^2) and 31–46% compared with concrete block (31.1 kg CO_2 eq/m^2). The best-performing formulations – CG5 (cork granules) and CT15 (ceramic tile waste) – achieve the lowest GWP, without environmental trade-offs. These results support the positioning of waste-based earthen products in the construction market and the development of Environmental Product Declarations for CEB wall systems.

Keywords: Compressed Earth Blocks (CEBs) · Environmental Sustainability · Life Cycle Assessment (LCA) · Industrial Waste Valorisation · Masonry Wall Systems

1 Introduction

The building sector accounts for approximately 36% of global final energy use and nearly 40% of total CO_2 emissions, associated with conventional materials like fired bricks and concrete [1]. Earthen construction, particularly compressed earth blocks (CEBs),

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has attracted interest as a low-impact alternative, combining mechanised production with ecological properties like low embodied energy and recyclability [2, 3]. However, wider adoption is hindered by functional limitations, specifically the trade-off between mechanical strength – relevant for both load-bearing and non-load-bearing walls – and thermal insulation for envelope elements [4].

To address this limitation, several optimisation strategies have been investigated, including particle size adjustment, alternative binders and the incorporation of natural or industrial materials [5, 6]. Among these, the use of industrial wastes and by-products is particularly promising, as it combines the environmental benefits of earthen construction with circular economy principles. Literature reviews confirm the technical feasibility of these approaches while highlighting the need for integrated assessments that simultaneously consider mechanical, thermal and environmental performance [5–7].

A critical gap in the existing literature concerns the environmental performance of functionally optimised CEB formulations incorporating industrial wastes and by-products. Within the scope of the BTCPro research project, four series of optimised residue-based CEBs were developed in collaboration with Betão e Taipa, a Portuguese earthen construction company based in southern Portugal. Each series incorporates a distinct waste or by-product: railway concrete waste (RC series), ceramic tile waste (CT series), cork granules (CG series), and waste tyre textile fibres (WTTF, TF series). Supported by a multi-criteria sustainability assessment (MARS-SC methodology [8]), the best-performing mixture in each series was identified at the block level in terms of the balance between functional, environmental and economic indicators. However, a wall-scale comparison is now required to fully characterise the environmental potential of these solutions in real construction applications.

Life cycle assessment (LCA) is the standard methodology for quantifying the environmental performance of building materials over their life cycle. In the Portuguese context, Fernandes et al. [3] conducted a cradle-to-gate LCA of CEBs and rammed earth produced by the same company, following the EN 15804 standard and using real production data from the company. Their wall-scale comparison showed that a 15 cm thick CEB partition wall achieves a global warming potential (GWP) of 16.6 kg CO_2 eq/m^2 and an embodied energy (EE) of 165 MJ/m^2, representing reductions of approximately 57% in GWP and 53% in EE relative to a ceramic hollow brick wall, and of 48% and 33% respectively relative to a concrete block wall. These results established a robust, reproducible baseline for earthen wall systems in Portugal and are widely cited as benchmarks in the field.

The present study addresses this gap by translating the block-level LCA data calculated during the BTCPro project to the wall scale, adopting the same functional unit (1 m^2 of partition wall), system boundary (cradle-to-gate, A1–A3) and inventory data for mortar and conventional walls as [3]. This approach reproduces the established methodological baseline and enables a direct and consistent comparison between the optimised waste- and by-product-based CEB solutions, the reference earthen wall, and conventional masonry alternatives. In doing so, it contributes a quantitative environmental basis for material selection in sustainable building design.

2 Materials and Methods

2.1 Environmental Performance Assessment

The environmental performance assessment is organised around the following impact categories: (i) Global Warming Potential (GWP); (ii) Ozone Depletion Potential (ODP); (iii) Acidification Potential (AP) for soil and water; (iv) Eutrophication Potential for marine (EPM), freshwater (EPF) and terrestrial (EPT) environments; (v) Photochemical Ozone Creation Potential (POCP); and (vi) Abiotic Depletion Potential of fossil resources (ADP_FF). Environmental indicators were quantified following the Life Cycle Assessment (LCA) framework defined by ISO 14040 [9] and the characterisation factors of the EN 15804:2012 + A2:2019 [10] reference standard for quantifying environmental impacts in building products.

2.2 Goal, Functional Unit, and System Boundary

The goal of this study is to quantify and compare the potential environmental impacts of five CEB-based partition wall solutions – a control sample (CS) and four optimised formulations – against two conventional partition wall systems – ceramic hollow brick and concrete block – in the Portuguese construction context. The CS consists of a mixture of local soil stabilised with 5% by volume of natural hydraulic lime (NHL5). The optimised CEB series each incorporate a different industrial waste or by-product at the volumetric proportion identified as optimal by the MARS-SC multi-criteria assessment: railway concrete waste (RC15, 15% v/v), ceramic tile waste (CT15, 15% v/v), cork granules (CG5, 5% v/v), and WTTF (TF7.5, 7.5% v/v).

For the environmental comparison, the functional unit is 1 m^2 of interior partition wall, meeting the requirements for residential dwellings in Portugal. This definition is consistent to that adopted by [3], ensuring direct comparability of results and a like-for-like benchmarking against conventional masonry systems. The system boundary is cradle-to-gate (modules A1–A3): raw material supply and transport to the production site, and manufacturing. Wall assembly and end-of-life stages are excluded.

2.3 Selection of CEB Formulations

From the experimental campaign carried out within the BTCPro project, three mixtures per series were produced and evaluated. The best-performing mixture from each series was selected for the wall-scale assessment based on the overall Sustainability Score (NS) achieved by the MARS-SC multi-criteria assessment – an integrated indicator encompassing functional, environmental and economic dimensions – under the scenario reflecting real-world transport distances in the Portuguese context. The selected formulations and their key characteristics per block are presented in Table 1. While thermal conductivity and unit cost are reported only for reference, the present study focuses exclusively on performance in the environmental dimension.

Table 1. Selected CEB formulations and key performance indicators per block.

Series	Mix	GWP [kg CO_2 eq]	λ [W/mK]	σc [MPa]	Cost [€]
Baseline (Control, CS)	CS	0.479	0.65	1.84	0.16
Railway Concrete	RC15	0.526	0.68	2.12	0.18
Ceramic Tile	CT15	0.435	0.59	2.29	0.15
Cork Granules	CG5	0.402	0.52	1.89	0.24
WTTF	TF7.5	0.480	0.53	2.41	0.16

GWP = Global Warming Potential; λ = thermal conductivity; σc = compressive strength.

2.4 Wall Inventory

Table 2 addresses inventory of all wall scenarios per functional unit. All CEB wall solutions consist of a single leaf of blocks in a 15 cm configuration (block width = 150 mm), with earth mortar joints. The blocks have standard dimensions of 300 mm × 150 mm × 80 mm, yielding approximately 36 blocks per m^2 of wall after accounting for 10 mm mortar joints in both height and length directions, consistent with the geometry of the blocks produced by Betão e Taipa.

Table 2. Material inventory per functional unit (1 m^2 of partition wall).

Inputs	Units	Wall Solution						
		CEB wall (15 cm)					Ceramic brick (15 cm)	Concrete block (14 cm)
		CS	RC15	CT15	CG5	TF7.5		
CEB	kg/m^2	250.9	246.9	233.6	239.1	230.5		
Earth mortar	kg/m^2	38.9	39.2	37.3	37.2	38.4	–	–
Ceramic hollow bricks	kg/m^2	–	–	–	–	–	63.6	–
Concrete blocks	kg/m^2	–	–	–	–	–	–	90.6
Cement mortar	kg/m^2	–	–	–	–	–	92.5	88.6

The earth mortar for block laying consists of a soil–lime mixture applied without render, following the company's standard practice and the composition documented by [3]. The mortar quantity per m^2 of wall was calculated from the number of blocks required to fill the functional unit. The mass of blocks per m^2 is the product of the number of blocks (36) and the average dry mass per block for each series, estimated from the bulk density measurements. For the conventional wall solutions – ceramic hollow brick (15 cm) and concrete block (14 cm) – the complete material inventory is taken directly from [3].

2.5 Life Cycle Impact Assessment

The life cycle of the CEB mixtures was modelled using SimaPro v9.5.0.0 software. Environmental impact characterisation followed the EN 15804:2012 + A2:2019 framework, using the Ecoinvent v3.9.1 database for all background inventory processes. The environmental impacts of the ceramic brick, concrete block and cement mortar systems were calculated from generic inventory data in the same database, ensuring consistency across all wall solutions.

3 Results and Discussion

3.1 Wall-Scale Environmental Performance

Table 3 provides the full environmental impact profile per m^2 of partition wall for all solutions across the eight impact categories assessed. Table 4 summarises the main indicator (GWP), together with the percentage reductions compared with conventional alternatives.

Table 3. Environmental impact categories analysed and for each m^2 of wall partition solution investigated.

Mixture	CS	RC15	CT15	CG5	TF7.5	Ceramic brick	Concrete block
GWP	1.97E+01	2.15E+01	1.81E+01	1.69E+01	1.98E+01	3.44E+01	3.11E+01
ODP	2.35E-07	2.76E-07	2.10E-07	2.14E-07	2.38E-07	3.54E-07	1.30E-07
AP	5.95E-02	6.45E-02	5.38E-02	5.44E-02	5.98E-02	9.10E-02	9.65E-02
EPM	2.08E-02	2.24E-02	1.87E-02	1.90E-02	2.09E-02	2.56E-02	2.72E-02
EPF	1.84E-03	1.94E-03	1.70E-03	1.71E-03	1.83E-03	4.31E-03	4.44E-03
EPT	2.26E-01	2.43E-01	2.04E-01	2.06E-01	2.28E-01	2.87E-01	3.07E-01
POCP	7.80E-02	8.57E-02	7.01E-02	7.13E-02	7.85E-02	9.51E-02	8.93E-02
ADP_FF	1.80E+02	2.06E+02	1.62E+02	1.64E+02	1.82E+02	2.28E+02	1.66E+02

Units: GWP [kgCO2eq]; ODP [kg CFC-11eq]; AP [mol H+ eq]; EPM [kg N eq]; EPF [kg P eq]; EPT [mol N eq]; POCP [kg NMVOC eq]; ADP_FF [MJ]

Table 4. GWP per functional unit (1 m^2 partition wall) and percentage reductions versus conventional walls.

Wall solution	GWP [kg CO_2 eq/m^2]	*vs* ceramic brick	*vs* concrete block
CEB wall CS	19.7	−43%	−36%
CEB wall RC15	21.5	−38%	−31%
CEB wall CT15	18.1	−47%	−42%

(*continued*)

Table 4. (*continued*)

Wall solution	GWP [kg CO_2 eq/m^2]	*vs* ceramic brick	*vs* concrete block
CEB wall CG5	16.9	−51%	−46%
CEB wall TF7.5	19.8	−43%	−36%
Ceramic brick (15 cm)	34.4	—	+11%
Concrete block (14 cm)	31.1	−10%	—

All CEB wall solutions present substantially lower environmental impacts than both conventional alternatives across all eight impact categories. In terms of GWP – the most climate-relevant indicator – the optimised CEB walls range from 16.9 to 21.5 kg CO_2 eq/m^2, compared with 34.4 kg CO_2 eq/m^2 for ceramic hollow brick and 31.1 kg CO_2 eq/m^2 for concrete block. Reductions range from 38 to 51% relative to ceramic brick and from 31 to 46% relative to concrete block. The same ordering is preserved across all other categories: CEB walls systematically outperform their conventional counterparts in ODP, AP, EPM, EPF, EPT, POCP, and ADP_FF, with reductions of comparable magnitude.

The acidification potential (AP) and marine eutrophication potential (EPM) of all CEB walls are dominated by the hydraulic lime content, which is the primary production-stage input. For CT15, where 15% of soil is replaced by locally sourced ceramic tile waste, both AP and EPM are the lowest among all evaluated solutions (0.054 mol H^+ eq/m^2 and 0.019 kg N eq/m^2 respectively), reflecting the reduction in lime and soil quantity per block. The same driver explains the lowest ADP_FF of CT15 (162 MJ/m^2), representing a 29% reduction versus ceramic brick. CG5 achieves the lowest GWP (16.9 kg CO_2 eq/m^2) due to the minimal transport burden of its low-density cork additive, but its ODP value (2.14×10^{-7} kg CFC-11 eq/m^2) is marginally higher than CT15, as the absolute reduction in soil mass is smaller at the 5% substitution level.

3.2 Comparison Between Optimised Formulations

CG5 achieves the lowest GWP among all evaluated solutions, 14% below the control sample wall (CS). This result reflects the partial substitution of soil by low-density cork granules: at 5% by volume, the reduction in soil and lime mass per block lowers all production-stage impacts, while the very low density of cork (~75 kg/m^3) keeps transport emissions negligible even at longer sourcing distances.

CT15 achieves the lowest values in seven of the eight impact categories and ranks second in GWP. The low environmental performance of CT15 is driven by the local sourcing of ceramic tile waste from the vicinity of the producing company (transport distance: 30 km) and the null production-stage burden allocated to CDW under ISO 14040 [9]. The 15% soil replacement is sufficient to reduce total lime and soil consumption per block, lowering all material-intensive impact categories simultaneously.

TF7.5 achieves a GWP and ADP_FF profile essentially equivalent to the control sample, since WTTF is incorporated as a volumetric additive rather than a soil substitute, introducing a small but consistent incremental burden across all indicators.

RC15 presents the highest GWP among the CEB walls (21.5 kg CO_2 eq/m^2) due to the long transport distance for railway concrete waste (195 km), which, combined

with the high density of the material, result in greater transport-related impacts. This transport penalty propagates consistently across all eight indicators, making RC15 the least environmentally favourable CEB solution under real-world sourcing conditions. Under a hypothetical scenario in which railway concrete waste is sourced regionally (30 km), this ranking could be reversed, as the transport contribution would be reduced to a level comparable to that of CT15.

A notable feature of these results is the high cross-category consistency of the ranking: CT15 and CG5 occupy the top two positions in virtually every impact category, while RC15 consistently ranks last among the CEB solutions. This coherence across GWP, ODP, AP, EPM, EPF, EPT, POCP and ADP_FF indicates that the environmental drivers are fundamentally the same – lime and soil mass per block, and transport distance of incorporated residue – and that optimising for one indicator implicitly improves the others. There is therefore no environmental trade-off between categories in the choice of CEB formulation, which simplifies decision-making for practitioners.

4 Conclusions

This study presents a wall-scale LCA comparison of optimised compressed earth block partition walls incorporating industrial wastes and by-products, benchmarked against conventional ceramic brick and concrete block walls in the Portuguese construction context. The main conclusions are:

- All five CEB wall solutions outperform both conventional alternatives across all eight impact categories assessed. GWP reductions relative to ceramic hollow brick range from 38 to 51%, and 31 to 46% relative to concrete block, confirming the environmental advantage of earthen walls over conventional masonry.
- CG5 achieves the lowest GWP (16.9 kg CO_2 eq/m^2), 14% below the control sample. The minimal mass and very low density of cork granules per block make the transport contribution negligible, even at longer sourcing distances.
- CT15 achieves the lowest values in seven of the eight impact categories (wall-scale-related), while also offering competitive compressive strength (2.29 MPa), thermal conductivity (0.59 W/mK) and unit cost per block. It represents the most balanced formulation for general-purpose earthen partition walls in Portugal.
- TF7.5 achieves environmental performance equivalent to the control sample across all categories, while offering the highest compressive strength (2.41 MPa) and one of the lowest thermal conductivities (0.53 W/mK) and prices (€0.16) at block scale, making it suitable for applications where structural performance is the primary requirement.
- RC15 presents the highest impact among CEB solutions due to real-world transport distances. However, local sourcing would bring its performance closer to CT15, confirming that logistical optimisation is critical to unlocking the environmental potential of railway concrete waste.

These findings provide a quantitative basis for the market positioning of optimised earthen products and support the development of Environmental Product Declarations (EPDs) under EN 15804. Future work should extend the system boundary to cradle-to-grave, incorporating operational energy savings from improved thermal performance

and the benefits of closed-loop recycling, further enhancing the environmental advantage of earthen wall solutions.

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Circular Economy Practices in Construction Projects: A Study of the Literature

Flávia Luisa Pires Enembreck[1](✉), Maria do Carmo Duarte Freitas[1], Luis Bragança[2], Sergio Fernando Tavares[1], and Gabriel Benachio[3]

[1] Universidade Federal do Paraná, Curitiba, Brazil
flaviaenemb@gmail.com
[2] Universidade do Minho, Braga, Portugal
[3] The University of British Columbia, Vancouver, Canada

Abstract. The construction industry is known for its environmental impacts, high consumption of natural resources, and waste generation. The introduction of circular economy (CE) principles is considered a strategy to achieve increasingly sustainable projects. This research reports on circular economy practices found in the literature for construction projects and highlights recent practices investigated from previously published surveys. The chosen technique was a systematic literature review from 2020 to early 2023 and a content analysis for data processing. This article presents a summary of the innovations and trends found in the review. Twelve new circular economy practices in civil construction were identified, highlighting the fundamental role of digital technologies—such as BIM, Digital Twins, and Artificial Intelligence—and projects focused on energy efficiency. The authors correlate these practices with the life cycle stages of the EN 15804 standard and the 10 Rs of sustainability, demonstrating the priority of the actions of "Rethink," "Reduce," and "Reuse." In addition to cataloging methods such as the use of bio-based materials and on-site waste management, the text points out gaps in the practical applications of methodologies such as DfAD (Design for Assembly, Adaptability, and Disassembly). In short, the work offers an initial overview of scientific progress in the transition from linear value chains to sustainable and technologically advanced construction models. Finally, the study presents an initial view of recent advances in the transition to a circular economy in the construction industry during the indicated period and offers suggestions for future research in this area of knowledge.

Keywords: Circular practices · Construction industry · Digital technologies · Energy efficiency · Sustainability

1 Introduction

The construction sector consumes a considerable amount of natural resources, produces high volumes of waste and causes a range of negative environmental impacts, including carbon emissions. These challenges are inherent in traditionally adopted linear value chains (Ajayebi et al., 2021). It is estimated that the construction area consumes around

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3 billion tons of natural resources annually, which represents a costly environmental impact. According to research conducted by the World Resources Institute, the construction industry accounts for 40% of total waste generated on a global scale. To address this problem and reduce the inefficient use of resources, CEPs need to be adopted in construction projects (Hassan et al., 2023).

The circular economy has emerged as a promising approach to drive sustainability and is typified as a strategy towards achieving more sustainable buildings in the construction industry (Cellucci, 2021). Adopting the EC is geared towards realizing sustainable development, which benefits the environmental, economic and social dimensions (De Oliveira Neto et al., 2022). However, implementing the concept of circular construction is still in the development phase (Hassan et al., 2023).

The importance of the topic has driven the development and discovery of knowledge, particularly globally in the area of civil construction. Benachio et al. (2020) investigated the development of the circular economy (CE) from 2015 to 2019 based on a literature review and compiled a list of practices observed in construction projects, cited by the authors of the publications analyzed. The study, in addition to being pioneering in the technical literature on circular economy in Brazil, is also an international reference with hundreds of citations in several high-impact journals.

The construction industry is recognized for its significant environmental impact, high consumption of natural resources, and excessive generation of waste. Traditionally, adopted linear value chains result in inefficient resource use and carbon emissions. Despite its importance, the implementation of the circular construction concept is still in the development phase.

The current research seeks to explore the advances published between 2020 and the beginning of 2023 to update knowledge on Circular Economy Practices (CEPs) in the Architecture, Engineering and Construction (AEC) sector.

The objective of this study is to systematically analyze scientific advances and emerging practices related to the circular economy in the AEC sector, focusing on publications produced after Benachio et al. (2020). The research aims to update the list of CEPs by exploring recent research while aligning them with the international standard EN 15804 and the 10 Rs of sustainability.

2 Research Method

This study adopts a systematic literature review approach based on a structured and replicable search strategy to identify recent scientific contributions related to circular economy practices in the construction industry. The review followed a structured systematic search protocol, including the definition of the research question, database selection, keyword definition, application of eligibility criteria, and qualitative analysis of the selected studies. The methodological procedure expands the literature review conducted by Benachio et al. (2020), aiming to map the evolution of the field following the publication of their study.

The methodology included a search was performed in the Scopus, Science Direct, and Web of Science databases using the keywords “Circular economy” and “Buildings”. Data for this review update was collected through a full reading of the selected texts.

Simultaneously, a list was prepared of circular economy practices mentioned in the surveys to identify new CEPs applicable in construction projects. The practices listed were part of the categorization for content analysis according to Bardin's (1977) approach. The publications were thoroughly examined in order to delve deeper into the relevant topics and, subsequently, to discuss the knowledge related to the mapped practices (see Fig. 1).

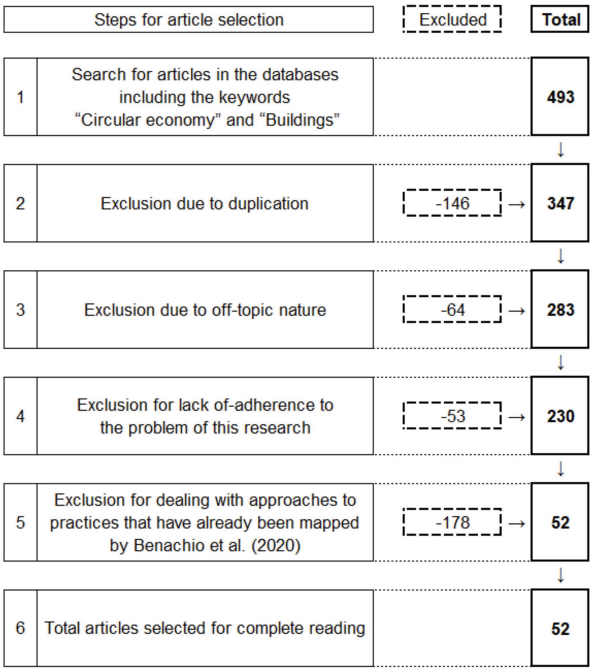


Fig. 1. List of articles by selection stage. Source: The authors (2026).

The Temporal Scope review covered publications from 2020 to the beginning of 2023. Articles were screened using the Rayyan web app. Out of 493 initial publications, 52 articles were selected for full reading after excluding duplicates, off-topic materials, and practices already mapped in the 2020 study (see Fig. 1).

After the complete reading of the selected articles, a table was prepared with the new practices described in a generic and broad way, which will be introduced and discussed following this article. Due to the limitations of the template, it will not be possible to present all the analyses obtained, such as the relationship between the new practices and the R's of the Circular Economy and the phases of the building life cycle.

3 Applied Analysis

The life cycle stages to which each measure refers were also updated according to the classification of EN 15804 described in Fig. 2.

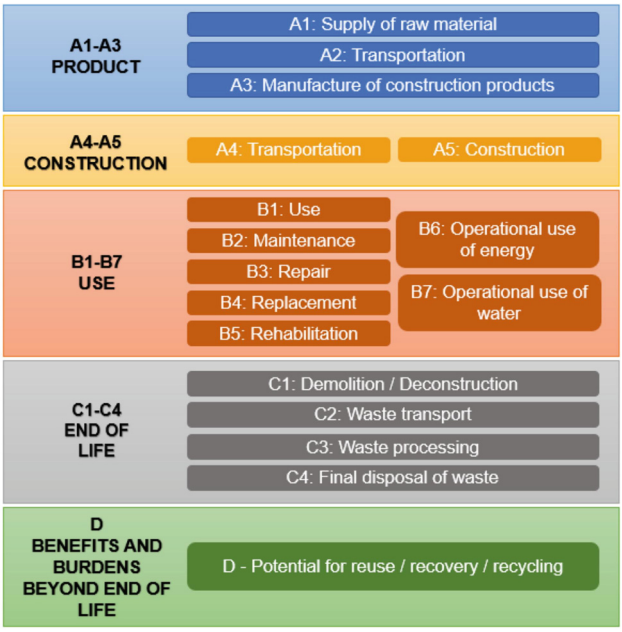


Fig. 2. Life cycle stages according to EN 15804. Adapted from CEN (2019).

A final analysis was made of the outcome to establish the connection between the CEPs identified in the literature and the main "R" of sustainability with which each aligns. This evaluation was based on the listing by Többen and Opdenakker (2022) and on the circular structure of the Rs in order of priority by Munaro and Tavares (2022), listing the 10 R's in the transition from the linear economy to the circular economy, as illustrated in Fig. 3.

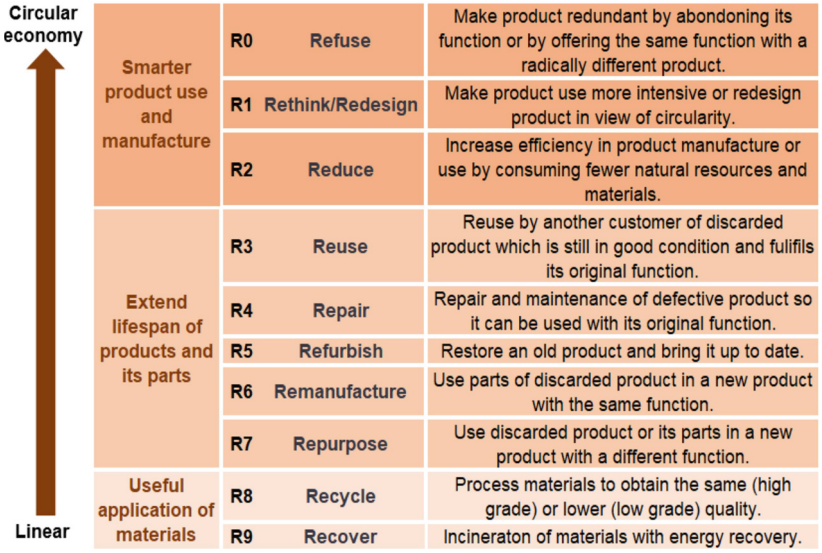


Fig. 3. List of the 10 R's of sustainability. Source: Adapted from Munaro and Tavares (2022) and Többen and Opdenakker (2022).

4 Contributions of Literature Review

The review made it possible to complement the list of CEPs for the built environment. Based on a complete reading of the 52 selected articles, 12 new construction CEPs were identified and compiled in Table 1, along with the respective authors who mentioned them.

In addition to Table 1, a qualitative content analysis was performed to gain a clearer understanding of the mapped practices, which will be presented below. This approach facilitated an in-depth grasp of the current state of practices in the literature, providing a more complete and detailed view of each of them.

Table 1. Additional circular economy practices in construction projects

Practice/CEP	Description	Author(s)
1. Use of digital technologies to help promote the circular economy	Digital technologies such as Internet of Things (IoT), BIM, robots, Artificial Intelligence (AI), 3D printing, blockchain, drones, and Augmented Reality (AR) have the potential to work alongside circular strategies… management of operations and optimization of material flows.	Akbarieh *et al.* (2020); Çetin *et al.* (2021); Jin *et al.* (2021); Lima *et al.* (2021); Medina e Fu (2021); Baduge *et al.* (2022); Caldas *et al.* (2022); Çetin *et al.* (2022); Gómez-Gil *et al.* (2022); Oviedo Hernandez *et al.* (2022); Setaki e Van Timmeren (2022); Yu *et al.* (2022); Giovanardi *et al.* (2022); Kaewunruen *et al.* (2023); Oluleye *et al.* (2023).
2. Use of bio-based materials	Biobased materials… are a sustainable alternative because they provide renewable supply chains and reduce carbon emissions through the natural process of carbon sequestration	Pujadas-Gispert *et al.* (2020); Dams *et al.* (2021); Oorschot e Asselbergs (2021); Besana e Tirelli (2022); Rabbat *et al.* (2022); Butt e Dimitrijevic (2022).
3. Design of energy efficiency	Energy efficiency projects are intended to reduce energy consumption over the life cycle of a building… optimizing the geometry and orientation, natural lighting and ventilation, efficient heating and cooling systems.	Foster *et al.* (2020); Franković *et al.* (2020); Li *et al.* (2020); Marconi *et al.* (2020); Mercader-Moyano and Escape (2020); Pujadas-Gispert *et al.* (2020); Rucinska *et al.* (2020); Antolinc and Filipič (2021); González *et al.* (2021); Ipsen *et al.* (2021); De Lucia *et al.* (2021); Majumder *et al.* (2021); Mercader-Moyano *et al.* (2021); Neri *et al.* (2021); Serrano *et al.* (2021); Mazzoli *et al.* (2022); Díaz-López *et al.* (2022); Oviedo *et al.* (2022); Piotrowska and Słyś (2023); Sadowski (2023).
4. Use of BIM for construction and demolition waste management	BIM is a tool that facilitates optimizing and reducing construction waste… compare different design layouts based on estimated waste production, promoting reuse and recycling.	Akbarieh *et al.* (2020), Copeland and Bilec (2020), Ganiyu *et al.* (2020), Hussien *et al.* (2021); Jin *et al.* (2021).

(*continued*)

Table 1. (*continued*)

Practice/CEP	Description	Author(s)
5. Use of BIM to improve operation, maintenance and asset management	During the operation and maintenance phase, the asset is continually monitored and updated based on the BIM model… tracking energy consumption and performance of components.	Abrishami and Martin-Duran (2021); Kaewunruen *et al.* (2023).
6. Using BIM for the deconstruction of buildings	Visibility and quality of existing physical assets are increased by the use of BIM, which makes it easier to anticipate specific demolition/deconstruction method. Environmental LCC analysis seeks a more	Akbarieh *et al.* (2020), Van den Berg *et al.* (2021); Charef (2022).
7. Modeling and application of Life Cycle Costing	comprehensive and holistic view of costs, including the external effects that can have a significant impact on economic and environmental sustainability.	Medina-Salgado *et al.* (2021).
8. DfMA approach in manufacturing and assembly design	Design for Manufacture and Assembly (DfMA) is a design approach that seeks to improve product manufacturing and assembly… to reduce costs, increase product efficiency and quality.	Abrishami and Martin-Duran (2021); Ipsen *et al.* (2021).
9. On-site waste recycling	Implementation of on-site waste recycling is essential to promote sustainable consumption… use of a robotic system to collect and classify construction and demolition waste on site	Wanaguru *et al.* (2022); Oluleye *et al.* (2023).
10. Management of hazardous materials	Pre-demolition auditing allows for the early detection of hazards… combined with source separation and on-site collection, makes it possible to plan selective demolition work.	Wu *et al.* (2022); Oluleye *et al.* (2023).

(*continued*)

Table 1. (*continued*)

Practice/CEP	Description	Author(s)
11. Use of local materials	Applying circular principles through the use of local construction techniques and materials… buildings offer well-suited solutions to local challenges, plus are more durable and sustainable.	Dabaieh *et al.* (2022).
12. Operational management of building space occupancy	Adaptive management of space based on dynamically changing usage needs… reducing the need for new construction and materials.	Mallis *et al.* (2021); Ruokamo *et al.* (2023).

Source: The authors (2026).

5 Main Findings and Discussion

Analyzing the complementary practices listed in the bibliographic review of this research, the most cited were found to be: use of digital technologies to help promote the circular economy and energy efficiency projects. A growing technological development has been recognized to support the implementation of circular economy principles in the built environment.

- Digital Transformation: There is a clear trend of incorporating Industry 4.0 technologies to stimulate CEPs, with digital technologies and energy efficiency being the most cited practices.
- Priority of Rs: The analysis showed that "Rethink" (28%), "Reduce" (19%), and "Reuse" (16%) are the most correlated strategies with the mapped practices. Over 53% of total practices refer to the top 3 priority Rs in the transition to a circular economy.
- Life Cycle Impact: The Product stage (A1–A3) remains the most impacted by circular practices, emphasizing the importance of predicting impacts during the design phase.
- Research Gaps: Gaps remain in the practical application of DfMA and LCC, as well as a lack of correlation with the "Restore" strategy.

The literature review identified new emerging practices, such as operational space management and the use of biobased and vernacular materials. These practices have gained traction in recent literature given their conversion to the circular economy by seeking to extend the useful life of buildings and reduce the negative impact on natural resources. In this scenario, compared to the current study, researchers were more concerned about the end-of-life phase of the building.

The energy efficiency project, pointed out as a practice in this research, is related to the circular economy based on the goal of reducing energy consumption and improving energy efficiency throughout the life cycle of buildings. The measures addressed in this

theme also refer to the reduction of greenhouse gas emissions, which provides for a more circular and sustainable approach in the construction sector.

There are, however, still some gaps in the research, especially regarding the practical application of approaches such as Design for Assembly, Adaptability and Desassembly (DfAD) and Life Cycle Cost (LCC). As for updating the life cycle stages according to EN 15804, it turned out that the product stage is more subject to interference from mapped circular economy practices.

The article also brought on an analysis of CEPs in relation to the 10 Rs of sustainability. The predominance of "Rethinking" as the main "R" associated with a greater number of practices highlights the frequent reassessment of processes and consumption patterns in CEPs and emphasizes the need for proper management throughout the life cycle of the construction project. Also, the significant correlations with "Reduce" and "Reuse" demonstrate how implementing these practices results in minimizing the consumption of resources and reducing the disposal of products in the industry. It was also noted that more than half of the practices focus on the three priority "R's" of the circular structure outlined by Munaro and Tavares (2022), illustrating the ability of these practices to strengthen the presence of the circular economy in the scope of construction project management.

6 Conclusions

This research sought, within the limitations of space, to incorporate new concepts and technological tools from the perspective of the Circular Economy in the Built Environment, based on the review by Benachio (2020). New technologies, their relationship to the 3 Rs of sustainability, and the phases and stages of the life cycle were observed in the current review and highlight sensitive points of change in the construction industry. Research in this area should be encouraged to seek alternatives to the scarcity of natural resources, raw materials, and energy, technologically improving, reducing costs, and minimizing the environmental impact of the construction industry in all its aspects.

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Deconstruction and Salvage of Light-Gauge Steel Partition Walls: Comparing Three Disassembly Approaches

Alexander Dhesi[1(✉)], Teresa Domenech[1], and Charnett Chau[2]

[1] Bartlett Institute for Sustainable Resources, University College London, London, UK
alexander.dhesi.24@ucl.ac.uk
[2] Saint-Gobain UK & Ireland, Coventry, UK

Abstract. This paper investigates the disassembly of light-gauge steel frame (LGSF) partition walls to assess component salvage feasibility. Disassembly of non-loadbearing partitions was observed in three contexts: typical demolition contractor strip-out, experimental deconstruction aiming to minimise steel damage, and a controlled disassembly trial at a manufacturer training academy. Data on process steps, equipment, labour, and timing were collected to compare the efficiency and effectiveness of the three approaches. Salvaged steel components from each trial were visually inspected and damage characterised. The study found that while the LGSF could be dismantled with minimal damage under controlled conditions, practical demolition site constraints and standard practices significantly impeded careful disassembly. Typical demolition strip-out prioritises rapid removal using heavy tools, causing significant steel deformation that likely prevents reuse. Access to connection points and influence of connected building components hindered interventions aimed at minimising damage. This research suggests that although circular economy and design for disassembly principles can deliver systems suitable for careful component recovery, such processes are neither time nor labour efficient in practice and would likely increase demolition contractor costs. These practical gaps between theoretical circular economy principles and actual demolition practices must be addressed to enable efficient and effective material recovery. The findings also highlight the need for further empirical research into how disassembly processes affect recovered steel condition and support material salvage and reuse outcomes.

Keywords: Light-gauge steel · Design for Disassembly · Circular Economy · Material reuse · Demolition practice

1 Introduction

Reuse in construction aims to prevent the early disposal of functional building materials and systems, supporting circular economy objectives by avoiding unnecessary consumption of replacement raw materials and energy [1, 2]. Fit-out systems like light-gauge steel frame (LGSF) partitions often undergo short installation, removal, and disposal cycles

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driven by space division changes and tenant turnover, rather than performance deterioration [3]. Strip-out and demolition practices prioritise rapid removal and minimal handling, often destroying components with residual functional performance [4].

LGSF systems are thin-walled galvanised steel profiles for constructing internal partition walls, external façade supports, and structural elements. They mostly feature mechanical connections (screws, bolts) and are often modularised for rapid installation. The design basis of LGSF systems is to provide mechanical support for insulation and plasterboard assemblies, dividing space or framing building structures and delivering acoustic insulation and fire resistance [5].

Despite the theoretical suitability of LGSF systems for disassembly and reuse [6–8], empirical evidence of material recovery outcomes under real demolition conditions is limited. This study compares LGSF partition disassembly across three contexts: a manufacturer training academy, an experimental deconstruction approach on a dormant demolition site, and typical strip-out operations on an active site.

Material reuse in construction depends on the ability to recover materials during strip-out and demolition without significant damage to components. Design-for-disassembly principles aim to enable component recovery through reversible connections, accessible fixings, and material separability [9]. However, the assumed effectiveness of design-for-disassembly relies on ideal deconstruction conditions that may not reflect practical demolition constraints [10].

Light-gauge steel frame (LGSF) systems are targeted for disassembly due to standardised components and reversible mechanical connections [6]. Previous studies demonstrate LGSF disassembly in experimental settings [7, 8], but empirical evidence from actual demolition operations is limited. The gap between controlled deconstruction studies and real demolition practice represents a critical barrier to recovering LGSF components for reuse.

Mayer [11] developed certification criteria for construction workers conducting material salvage operations, identifying key process indicators including site safety, tool requirements, deconstruction techniques and material handling protocols. Cabral et al. [12] assessed material recovery interventions through indicators including recovery rate, skill requirements, workplace constraints, and material preservation outcomes. Hradil et al. [13] proposed a framework for evaluating component reuse feasibility based on ease of deconstruction, handling, separation, quality checking, and geometry verification.

While existing frameworks establish criteria for assessing material recovery, empirical application in varying disassembly contexts is limited. This study addresses the gap by combining three assessment frameworks, comparing LGSF partition disassembly in training, experimental deconstruction, and typical demolition contexts.

2 Methodology

2.1 Framework Development

A three-part assessment framework was developed from existing material recovery evaluation methodologies to enable systematic comparison between disassembly contexts.

The first component addresses site features, tools and work sequences, drawing on deconstruction worker certification criteria to characterise safety requirements, equipment, site layout, and process steps [11]. The second component considers material salvage process interventions, assessing recovery rates, skill requirements, workplace constraints, labour demand, and material preservation outcomes [12]. The third component evaluates material condition and reuse feasibility, considering ease of deconstruction, handling, separation, quality checking, and geometry verification [13].

Three disassembly trials were conducted representing a progression from ideal to typical conditions. The training academy trial reflects ideal conditions: LGSF systems were installed and deinstalled by the same team, under the guidance of training staff; connection points were left accessible, and there were no time constraints on the steel recovery operation. The deconstruction trial took place on a dormant demolition site, where recovery activities attempted to minimise damage to steel components despite site constraints. The demolition trial observed standard strip-out practice on an active site, prioritising rapid partition removal using typical demolition tools and techniques.

All three trials considered the same LGSF partition system (British Gypsum Gypframe, Fig. 1), selected based on training academy availability and presence in the chosen demolition site, with components recovered for condition assessment.



Fig. 1. Gypframe non-loadbearing interior partition system, British Gypsum [14].

2.2 Data Collection and Analysis

Data collection combined observational methods, photography, timing estimates, and physical sample recovery and inspection. For each trial, disassembly process sequences were documented including tool and equipment use, labour requirements, safety measures, and approaches to handling removed materials. Approximate timing data were recorded based on observation of how long different process steps required. LGSF components were recovered from each trial, visually inspected and photographed to characterise defects including deformation, cut edges, connection zone damage, and screw holes.

Observational notes, photographs, videos and timing estimates recorded during each trial were retrospectively assessed against the three-part framework. Indicators were adapted from source frameworks [11–13] and interpreted individually based on observed

differences between trials: comparative ranking (High/Moderate/Low) were assigned to reflect the author's judgement of how the three approaches compared against each indicator.

3 Results

3.1 Site Features, Tools, and Work Sequences

The three disassembly approaches differed significantly in safety requirements, tooling, and site organisation (Table 1).

Table 1. Observational assessment of site features, tools, and work sequences [11]

Indicator	Training Academy	Deconstruction	Demolition
Site safety	Controlled training environment. Gloves, safety glasses, steel-capped boots.	Dormant site scheduled for demolition. Gloves, helmet, safety glasses, dust mask, steel-capped boots.	Active demolition site. Gloves, helmet, safety glasses, dust mask, steel-capped boots, overalls, ear defenders.
Tools	Impact driver, hammer.	Angle grinder, screwdriver.	Reciprocating saw, crowbar.
Site layout	Training bays with clear access.	Constrained by remaining building elements, limited staging area.	Constrained by demolition sequence, materials handled in situ.
Deconstruction techniques	Plasterboard removal, unscrewing, steel frame disassembly with impact drivers.	Plasterboard cutting, unscrewing, steel cutting with angle grinder.	Plasterboard cutting, steel frame destruction with crowbar.
Layered materials	Tape and joint materials only. Clear access to connection points.	Heavy timber skirting fixed through studs, suspended ceiling grid obstructing access.	Skirting and ceiling previously removed; connections accessible.
Debris handling	Full-length stud sections removed, waste segregated and recycled.	Cut stud samples removed.	Samples recovered from scrap steel segregation.

Deconstruction techniques varied from systematic unscrewing (training academy, Fig. 2a) to strategic cutting around obstructions (deconstruction, Fig. 2b) to rapid destructive removal (demolition, Fig. 2c). Critically, layered building elements, particularly the skirting board and suspended ceiling grid, prevented direct access to steel frame connection points in the deconstruction trial, necessitating cutting interventions that limited material recovery rates.





Fig. 2. Photographs showing (a) training academy, (b) deconstruction and (c) demolition trials in progress.

3.2 Material Salvage Process Interventions

The deconstruction trial resulted in the lowest material recovery rate due to severe workplace constraints that prevented effective intervention: inaccessible connection points, layered building elements, and limited staging area combined to undermine careful disassembly attempts (Table 2).

Table 2. Assessment of material salvage process interventions (High/Moderate/Low) [12]

Indicator	Training Academy	Deconstruction	Demolition
Material recovery rate	High	Low	Moderate
Skill level requirement	Moderate	High	Low
Workplace constraints	Low	High	Moderate
Safety risk level	Low	High	Moderate
Labour requirements	High	Moderate	Low
Operational flexibility	Low	Moderate	High
Material preservation	High	Moderate	Low

Interventions aimed at minimising steel damage in the deconstruction trial were limited by the need to cut through studs where skirting boards and ceiling grids prevented unscrewing, resulting in short sections being recovered for assessment.

3.3 Material Condition and Reuse Feasibility

Component condition assessment revealed that only the training academy trial yielded sections suitable for potential reuse (Table 3).

Table 3. Assessment of material condition and reuse feasibility (High/Moderate/Low) [13]

Indicator	Training Academy	Deconstruction	Demolition
Ease of deconstruction	High	Low	Moderate
Ease of handling	High	Moderate	Low
Ease of separation and cleaning	High	Moderate	Low
Ease of quality checking	High	Moderate	Low
Ease of geometry checking	High	Moderate	Low

Full-length (2400 mm) steel stud sections were recovered from the training academy trial with minimal damage beyond holes from screw connections (Fig. 3a). Deconstruction trial samples showed moderate handling and assessment feasibility, but incurred damage at cutting points and connection zones, especially where layered materials had been fixed to the steel studs (Fig. 3b). Demolition trial samples exhibited the lowest feasibility scores across all indicators due to severe deformation from crowbar use, sharp edges from cutting, and twisted sections that prevent safe handling and reassembly. The LGSF installation deviated from manufacturer specifications, with unnecessary fixings between studs and channels adding disassembly complexity (Fig. 3c).



Fig. 3. Photographs showing (a) full-length intact sections recovered from the training academy, with screws still attached; (b) damaged sections recovered from the deconstruction trial; (c) installation error fixing studs to head channel in demolition trial.

4 Discussion

4.1 Design Implications

The training academy trial demonstrates that LGSF components can be removed without severe deformation when connections are accessible and time is unconstrained, supporting findings from controlled disassembly studies [7, 8]. The deconstruction and demolition trials develop these findings to show how site constraints prevent careful removal in operational contexts.

Alternative connection designs could address specific damage modes. The use of screws in plasterboard fixing could be addressed through clips or interlocking boards.

Modular panel-based LGSF systems, designed to improve installation efficiency and reduce material waste, may offer an additional benefit for deconstruction by enabling removal of intact panels rather than components [10]. Any design intervention intended to improve recovery outcomes requires validation in comparative trials under site conditions.

Improper installation significantly affected the condition of recovered LGSF components: unnecessary screw fixings between studs and head channels prevented component disassembly and encouraged destructive removal. Standardised installation and deconstruction protocols provided by manufacturers or enforced through certification [11] could improve recovery outcomes but requires validation under typical project constraints.

4.2 Policy Implications

The dormant period between building vacation and active demolition in the deconstruction trial represents an under-utilised window for material recovery. Policy mechanisms like pre-demolition audits [4] or material recovery credits that encourage early contractor engagement and phased soft-strip works could facilitate careful component removal before time-critical strip-out phases begin.

5 Conclusions

This study compared light-gauge steel frame disassembly in three contexts: controlled training conditions, experimental deconstruction on-site, and typical demolition strip-out, revealing significant gaps between circular economy principles and demolition practice. Only the training academy trial yielded components in reusable condition; site constraints including layered building elements, time pressure, and installation errors prevented effective material recovery despite intervention attempts.

These findings demonstrate that design for disassembly principles are insufficient to optimise reuse outcomes without parallel changes to installation practices, demolition timelines, contractor capabilities, and economic incentives that currently prioritise speed over material preservation.

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Advancing Circular Economy and Decarbonisation in Infrastructure: The Case for Steel Sheet Piles

François Fohl(✉), Michael Bezzo, and Oliver Hechler

ArcelorMittal Sheet Piling, Esch-sur-Alzette, Luxembourg
francois.fohl@arcelormittal.com

Abstract. Infrastructure constitutes one of the largest global consumers of construction materials and a major source of embodied carbon emissions. Despite growing momentum toward a circular built environment, deep foundations and retaining structures remain domains in which circularity principles are insufficiently implemented, even though their potential is considerable. This paper examines how steel sheet piles - modular, reusable, recyclable, and increasingly optimised through digitalisation - provide a practical pathway with regards to a part of the 9R framework for reducing environmental impacts across the full life cycle of infrastructure assets. Refuse is addressed by structural health monitoring opportunities. Reduce is outlined through a Life Cycle Assessment showing that permanent sheet pile walls can achieve substantial CO_2e reductions when compared with conventional alternatives. The potential of structural optimisation using products with enhanced efficiency is analysed. Reuse and refurbish is examined by presenting an industrialised reuse model enabled by rental and refurbishment, offering multiple use of sheet piles and carbon savings. Finally, recycle is addressed by analysing how different steel production routes influence overall climate performance. Overall, the findings highlight the essential role of advanced circularity considerations for the decarbonisation in infrastructure.

Keywords: Circular economy · 9R · Steel Sheet Piles · LCA · Infrastructure

1 Introduction

The construction sector is progressively advancing the implementation of circular economy principles, yet adoption rates vary across domains. Infrastructure and deep foundation works, in particular, lag behind sectors such as housing in applying low carbon and circular construction practices. Infrastructure is the backbone of the built environment and subject to over €120 billion investment yearly only in Europe [1]. Considering the number of projects, in maritime, waterway or urban environments, infrastructure represents a big opportunity for applying circular economy principles, noting that in infrastructure, construction materials typically account for over 80% of a project's total carbon footprint [2]. Retaining walls are frequently employed in infrastructure and sheet

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piling is one technical solution. Sheet Piles are prefabricated and modular steel members, that are connected one to another with interlocks. As a consequence, they form continuous retaining walls that can be temporary or permanent with design life up to 120 years.

This paper will address parts of the 9R framework, and discusses, based on the keywords 'refuse', 'reduce', 'reuse/refurbish' and 'recycle', levers and opportunities on implementing circular economy. Focus lies on retaining walls and reduction potential on the so-called embodied carbon emissions, measured in CO_2-equivalents. Every Life Cycle Assessment (LCA) cited in this paper is based on product-specific Environmental Product Declarations (EPDs), whenever they were available. Highly impacting construction materials, such as steel or concrete, always refer to publicly available product-specific EPDs. The cited LCA modules are those defined by EN 15804+A2. Module B, representing the use stage, is generally not worth quantifying for infrastructure projects, as emissions are rather moderate compared to the overall environmental impact, given that infrastructure projects are generally not cooled or heated over the entire service life.

2 Service Life of Infrastructure

Highest degree of circularity can be achieved with a refuse approach, as this strategy avoids waste generation and the use of resources and energy. One way of interpreting the refuse strategy in the current context is to simply avoid the construction of new infrastructure. Certainly, not a viable and realistic option in most cases as infrastructure is essential for a working society (see railway stations, ports, dykes, bridges, etc.). A softer variant of the refuse strategy would be the extension of the service life of infrastructure, generally designed for 50–120 years depending on the different applications. Strict monitoring, as already implemented for bridges, can significantly extend the service life of structures. Taking the example of sheet pile retaining walls, there are concepts available that monitor the health state of the structure with specific sensors. The data is collected, synthesized and made available in a digital twin model, that can be assessed at any time. Preventive maintenance work can be scheduled or hidden capabilities revealed to ultimately extend the life of the structure. Furthermore, Artificial Intelligence helps to analyse the vast data and take data-driven decisions [3]. Lengthen the service life of infrastructure, can significantly reduce the pace of new constructions, hence reduce the use of construction materials.

3 Structural Optimisation of Retaining Walls

3.1 Choice of Construction Method

For a specific application, be it temporary or permanent, multiple technical solutions can be considered and are in many cases technically equivalent. The task of a consulting engineer is indeed to find the most adequate solution that fits the project's and project owner's needs on a technical and financial level. The technical catalogue of an infrastructure or deep foundation project can contain requirements on circularity and environmental impact of used construction materials. However, this is rarely the case.

The benefit of studying alternative solutions in reference to technical, financial and environmental criteria is demonstrated via an underground car park (UCP) example in a usual urban setup. The underlying technical design and financial assessment of the variants is carried out by the German consultant GRBV [4]. The study compares the following technical equivalent solutions: (V1) Permanent sheet pile wall; (V2) Temporary sheet pile wall in combination with a permanent reinforced concrete wall; (V3) Concrete secant piles; (V4) Permanent diaphragm wall/slurry wall. Figure 1a shows the variant with permanent sheet piling that encapsulates a 28 m × 28 m construction pit, accommodates the vertical loads of the 4-storey building above, and is designed for the entire service life of the structure. Like this, the retaining wall assures at the same time the need for a short-term construction pit and the long-term foundation wall.



a. Permanent sheet pile retaining wall **b.** Two-level UCP

Fig. 1. **a.** Permanent sheet pile retaining wall. **b.** Two-level UCP

The LCA, verified by a panel of 3 independent experts, considers the entire retaining wall (blue on Fig. 1b) as a functional unit and follows the principles of ISO 14040/44 and EN 15978 [5]. Over the entire life cycle (modules A-D) the permanent sheet pile wall is 58% less impacting in CO_2e than the secant pile solution (see Fig. 2).

As the steel solutions, both temporary and permanent, come out cheaper than the concrete alternatives, the optimisation potential towards circularity and low-carbon construction is given. The LCA considers the quantity of construction materials and related transport emissions. Nevertheless, not included are social by-impacts that are caused by the transport of the materials, generally disturbing in inner city areas. Variant 1 only needs 704 t of materials (concrete, steel, etc), variant 2 1,290 t, while variant 3 consumes 5,113 t and variant 4 4,881 t. The study demonstrates that the use of low-carbon, modular and prefabricated construction solutions can accelerate the move towards circular economy, without suffering from drawbacks on a financial basis.

3.2 Optimised Design

For sheet pile retaining walls, the optimisation, hence the reduction of needed construction materials starts with efficiently designed sheet piles. As a consequence of continuous

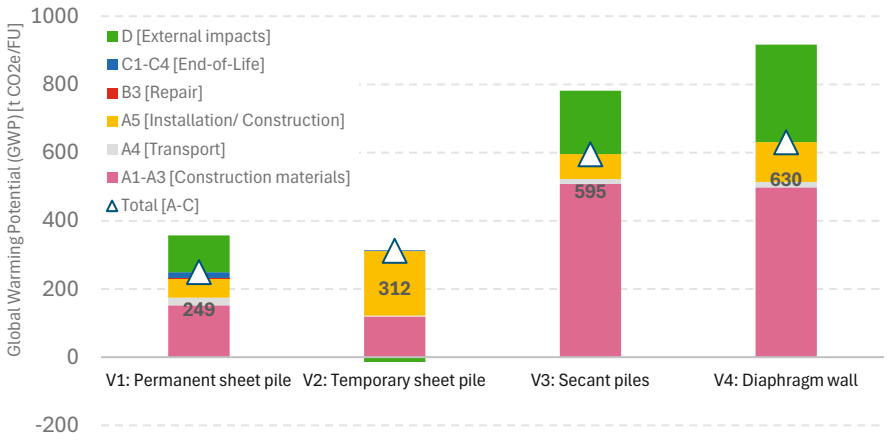


Fig. 2. Global Warming Potential caused by the retaining wall (FU/Functional unit)

improvements in production, profiles have become increasingly lighter while offering the same section modulus. New geometries, often wider, have enabled savings of up to 30% in steel mass over the last few decades. In terms of geometry, Z-shaped sheet piles are principally more efficient in surface mass (kg/m^2) than U-shaped profiles. In addition, Eurocode EN 1993-5 doesn't consider for a reduction factor (β_B) for Z-shaped profiles, as the interlocks are located far from the neutral axis, and are not subject to shear stresses. The second lever for optimising the sheet pile solution is the steel grade. The production standard for hot-rolled sheet piles EN 10248:2023 includes grades up to 500 MPa in yield strength. The rule of thumb says that the choice of a higher steel grade allows the choice of a lighter profile, leading to more economical solutions with reduced carbon footprint. A dyke reinforcement project in Dax, France, shows the potential of structural optimisation. The design study had foreseen a PU 18 profile. The contractor optimised towards a Z-shaped profile and installed an AZ 14-770. By avoiding the reduction factor β_B, the contractor was able to save 20% in steel mass, embodied emissions and cost, while still meeting the same safety level [6]. For permanent projects, Z-shaped profiles should be considered right from the beginning, leading to substantial savings in CO_2e in the projects. Still, U-shaped profiles remain the preferred choice for temporary projects. They are perfectly adapted to be reused several times (5–10×).

4 Reuse of Steel Sheet Piles: Operational and Business Model

Approximately 40 years ago, ArcelorMittal introduced the concept of sheet pile rental, further strengthening the competitive position of steel sheet piles in comparison with alternative construction methods, such as concrete. This rental-based business model was established for its steel sheet pile portfolio to generate benefits for both, customers and the environment. The rental model for steel sheet piles offers companies undertaking excavation projects a cost-efficient and logistically streamlined alternative to purchasing materials. By reducing capital immobilisation, and simplifying handling processes, the rental approach yields notably lower costs per square meter of retaining structures

compared with systems relying on other substitute materials. The repeated reuse of steel sheet piles across multiple construction projects exemplifies a practical and robust circular economy model within the infrastructure sector. This practice extends the service life of steel components, optimises material utilisation, and reduces demand for primary resources. ArcelorMittal operates a network of specialised service centres that function as logistical and operational hubs within its steel sheet pile rental system. These centres are responsible for the acquisition, assessment, refurbishment, inventory management, and redistribution of sheet piles, thereby ensuring a continuous and quality-assured material flow. Upon entry into the system, both new and previously used sheet piles undergo a structured evaluation process in which their condition is assessed and documented through an internal protocol. Subsequent cleaning, inspection, and repair activities restore the piles to the technical and performance standards required for redeployment. Once refurbishment is completed, the sheet piles are inventoried in batches characterised by profile, steel grade, and length. When a rental request is received, material from the corresponding batch is dispatched to the construction site. If existing stock does not fully satisfy the project specifications, additional piles from other batches are adapted to meet the order requirements. Rental fees are collected monthly, with a proportion allocated to covering operational and overhead costs of the service centre, while the remaining share contributes to the depreciation of the rented material. Following completion of the project, the sheet piles are returned to the service centre, where they undergo a renewed cycle of assessment, refurbishment, and reintegration into inventory. Depending on the extent of required maintenance, returned piles may be reassigned to a different batch. Costs associated with repairs, maintenance, or losses are charged to the customer. This closed-loop operational model (see Fig. 3) prolongs the effective service life of steel sheet piles and represents a practical implementation of circular economy principles within the construction sector.

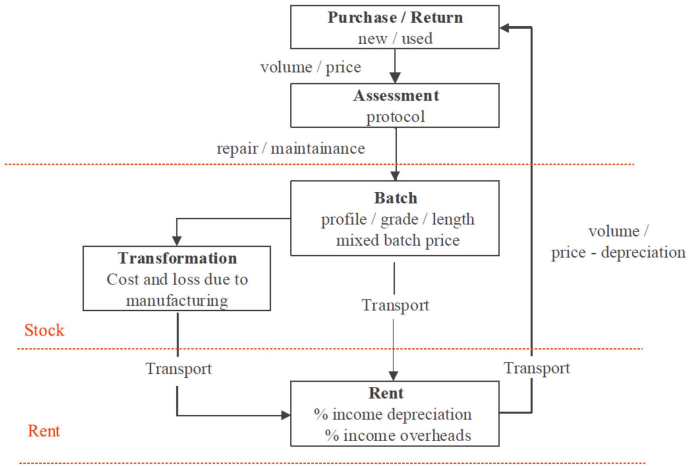


Fig. 3. Closed-loop operational model for sheet pile rental

The composition of the stock inventory is consistent to reflect region-specific geological conditions and the corresponding utilisation segments, which determine the expected loading and thus define required profile types and lengths. Only steel sheet piles from ArcelorMittal's product portfolio are held in stock, uniformly in steel grade S355GP. To guarantee the safe reuse of steel sheet piles, their conformity with the relevant product and manufacturing standards must be verified prior to re-introduction into the market. In the context of sheet piling works, structural design follows EN 1993-5, while steel sheet piles themselves are governed by the product standard EN 10248. Consequently, any reused sheet pile must undergo an assessment confirming compliance with EN 10248, and the resulting conformity documentation must be retained. This procedure provides the necessary assurance that reused elements meet the requisite mechanical and quality standard for safe employment in new construction projects. To ensure the reliable functioning of the sheet pile rental system, the company has implemented a structured quality-control procedure within its stocking facilities. Upon return of rented material or acquisition of used piles, a reception report is issued to the customer. The sheet piles are subsequently subjected to an initial cleaning process, during which surface contaminants are removed and the interlocks are thoroughly cleaned in order to allow for a precise visual assessment (see Fig. 4b). Thereafter, the geometric conformity of each pile is verified against the dimensions prescribed in EN 10248, enabling accurate classification of the returned elements with respect to profile and length. Any deviations from the standard geometry, as well as the repair measures required to restore compliance, are recorded in a reception protocol. This document incorporates photographic evidence of observed defects and provides an itemized overview of the refurbishment costs. Based on a cost-benefit evaluation, a decision is taken on whether a pile will be refurbished or scrapped.



a. Sheet pile before washing **b.** Sheet Pile after washing

Fig. 4. **a.** Sheet pile before washing. **b.** Sheet Pile after washing

Refurbishment tasks necessary to regain compliance with EN 10248 are executed in accordance with EN 12063, encompassing operations such as cutting, straightening, and welding. All interventions are documented and appended to the reception report, together with the corresponding invoicing information issued to the customer or job site. Following completion of the refurbishment process, the material is re-entered into inventory within the appropriate batch (see Fig. 5). Any customer inquiries or requests for inspection are addressed as part of the established procedure.

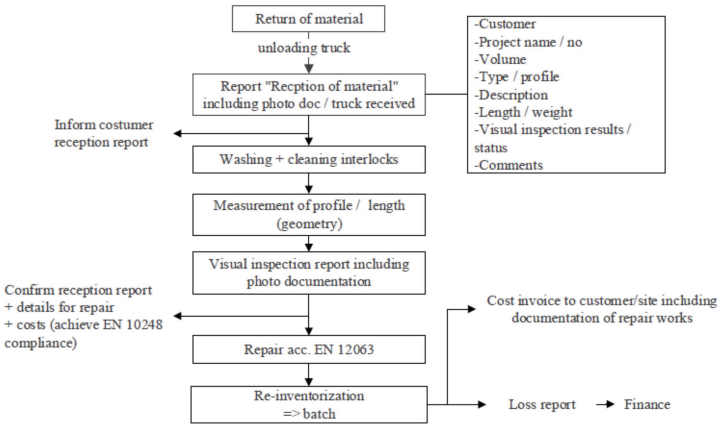


Fig. 5. Workflow for sheet pile rental business

This sheet pile rental model constitutes a utilisation-oriented business approach in which customer value is derived from access rather than ownership, enabling broader market reach and enhanced revenue generation from a single asset base.

To further decarbonise infrastructure projects, the rental stocks are composed of sheet piles made via the Electric Arc Furnace route, and use of renewable electricity (XCarb®). As an example, a construction pit in Germany used 798 t of rented sheet piles. Considering 5 reuse cycles with subsequent recycling of the steel, the allocated carbon footprint for this project is 104 t CO_2e, instead of 520 t CO_2e in modules A-D [7]. By reducing the need for new production, this model simultaneously alleviates environmental pressures and lowers resource consumption, thereby demonstrating that steel reuse is both technically feasible and commercially viable.

5 Recycling of Steel in Construction

Steel is the most recycled material in the world, mainly driven due to the inherent properties of steel enabling easy sorting. Especially the steel used in construction is nearly entirely recycled with recycling rates of 92% and a reuse rate of 4% for all construction steels (rebars, sections etc.) [8]. For sheet piling, surveys note around 60% of the initial tonnage recycled and 25% reused after the first use. Once collected at the end of the service life, the sheet piles, as well as other steel materials, are resources again, as every steel production route uses pre-consumer and post-consumer scrap. Especially the Electric Arc Furnace (EAF) route uses 100% scrap input. This recycling process does not rely on iron ore and/or coal to produce new steel products. Due to its properties, steel is recyclable without losing its characteristics. Moreover, steel production based on steel scrap allows for a drastic reduction of the carbon footprint of the new steel. Hereunder the average emissions (Modules A1-A3) of one ton of crude steel depending on the production route [9, 10]:

- Blast Furnace/Basic Oxygen route (BF/BOF): 2,300 kg CO_2e/t

- Direct Reduced Iron route (DRI): 1,100 kg CO_2e/t
- Electric Arc Furnace route (EAF): 400 kg CO_2e/t

An LCA study for a ferry terminal in Calais, France, inaugurated in 2021, showed that a HZ-M combi wall (EAF route) instead of a tube combi wall (partially BF/BOF route) saved 14,575 t of CO_2e in modules A1-A3 and 2,607 t of CO_2e in modules A-D [11]. The choice of the steel production route of the constituent steel members in a project is an important factor in reducing the overall environmental impact of infrastructure.

6 Conclusion

The application of selected R-strategies of the 9R circularity framework to infrastructure and deep foundation works reveals significant opportunities to enhance circularity and lower embodied carbon in retaining wall construction. Structural health monitoring evidence shows that extending service life effectively avoids carbon intensive new construction. Life Cycle Assessment results further demonstrate that optimised steel sheet pile walls markedly outperform conventional concrete alternatives. An established business model for reuse and refurbishment confirms that circular practices are technically mature and operational at scale, yielding measurable environmental benefits. Overall, steel sheet piling emerges as a proven and impactful pathway for advancing decarbonisation and circularity in global infrastructure projects.

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Upfront Carbon and Circularity Assessment of a Modular UK Residential Building

Fabio Goncalves, Ana Bras, and Michaela Gkantou(✉)

BEST Research Institute, School of Engineering and Built Environment, Liverpool John Moores University, Liverpool, UK
m.gkantou@ljmu.ac.uk

Abstract. Modular construction is increasingly recognised as a low-carbon building approach due to its manufacturing efficiency, reduced waste generation, and potential to support circular material flows. This study evaluates the upfront embodied-carbon and circularity performance of a modular steel dwelling in Northwest England using an enhanced A0–A5 Upfront Carbon Tool developed by Liverpool John Moores University. Built based on the IStructE Structural Carbon Tool, the enhanced framework incorporates Low Energy Transformation Initiative (LETI)-aligned benchmarks, an expanded Environmental Product Declaration (EPD) database, whole-building assessment, and circularity metrics based on reusability and recyclability potential. A scenario-based analysis compares a baseline design with an optimised alternative using locally available low-carbon materials. The optimised scenario achieves a 28% reduction in upfront embodied carbon (A0–A5) while maintaining high circularity levels (≈72% reusability, 93% recyclability), demonstrating that carbon reduction and circularity can be achieved simultaneously through early-stage material substitution. The findings demonstrate that modular construction, when combined with early-stage material optimisation and whole-building carbon assessment, can simultaneously enhance circularity and reduce embodied impacts. The study highlights the need for standardised recyclability indicators within EPDs and improved reuse certification frameworks to further support circular-economy adoption in the construction sector.

Keywords: Low-carbon · circular economy · carbon tool · reusability · recyclability

1 Introduction

The construction sector is widely recognised as one of Europe's most resource-intensive and waste-generating industries, with the built environment accounting for around 50% of all extracted materials [1, 2] and almost 40% of annual waste [3, 4]. These figures highlight the growing urgency to minimise waste, improve material efficiency, and accelerate the transition to a more circular construction economy. In response to these challenges, modular construction and broader Modern Methods of Construction (MMC) have emerged as key approaches for increasing productivity and reducing environmental

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impacts [5–7]. By shifting activities to controlled factory environments, MMC reduces construction errors, improves quality, streamlines supply chains, and significantly cuts waste compared with traditional on-site methods, positioning modular systems as a central component in European circularity strategies [6].

As operational emissions decline due to stricter energy standards, the relative importance of embodied carbon has increased, with construction materials and activities contributing nearly 40% of total greenhouse gas emissions [8, 9]. Life Cycle Assessment (LCA) therefore plays a vital role in quantifying environmental impacts and guiding low-carbon design choices. Improving material reuse and recycling—supported by selective demolition, standardised sorting, and greater confidence in recycled materials—can substantially reduce virgin material extraction and associated emissions. In parallel, design-for-disassembly and modular components enable buildings to function as material banks, extending material lifespans and reducing reliance on primary resources.

The present study applies LCA to a modular house in the UK to evaluate and optimise its environmental performance, while also evaluating its reuse and recycling potential in line with LETI [10] and EU targets [11]. The selected case study is presented in Sect. 2, the methodology and results in Sects. 3 and 4, respectively, and the final conclusions in Sect. 5.

2 Case Study

The case study building is a 99 m^2 semi-detached 3-storey dwelling located in Brooklands UK. It was designed and manufactured by the modular construction specialist Starship Group [12]. The dwelling contains 3 bedrooms, living area, kitchen and 2 bathrooms, representing a typical contemporary family home in the UK. Figure 1 presents some photos of the completed building.

The building perimeter walls are founded on reinforced concrete (RC) ground beams, which are supported on RC piles. On top of the RC ground beams sits a ground slab. The main superstructure is prefabricated Light Gauge Steel Framing (LGSF) including all



Fig. 1. Modular construction case study – Brooklands Building, Wirral Waters, UK [13].

walls, suspended slabs and roof. The core of the LGSF is infilled with thermal insulation (rockwool at internal face and Polyisocyanurate (PIR) at external face). Vapor barriers were installed on the inner faces of the façade walls as moisture control solution. The building's facade is protected by a brick slip system, and the roof is protected by cement thin flat tiles. The interior side of façade walls and ceilings are composed of plasterboard, and the floors finish is carpet. Internal walls consist of steel studs with optional mineral wool infill and plasterboard on both sides. The windows are triple-glazed plastic frames, and the interior staircases were made of wood. The floor layouts are presented in Fig. 2.



Fig. 2. Floor Plan Sketches – Brooklands Building, Wirral Waters, UK [13]

3 Methods

Liverpool John Moores University (LJMU) has developed an enhanced Microsoft Excel–based Upfront Carbon Tool to support construction professionals in estimating embodied carbon across stages A0–A5, covering all emissions before a building becomes operational, including A0 (pre-construction activities such as site preparation and temporary works) and A1–A5 (product manufacturing, transport, and construction). Built based on the IStructE Structural Carbon Tool [14], the LJMU tool adds LETI-aligned benchmark scoring, an expanded EPD database (with country of manufacture), and full structural and non-structural coverage. It introduces A5.4 worker-transport emissions and strengthens circularity through reusability and recyclability metrics. Carbon reporting is simplified to whole-building level, the Comparisons tab now includes 2030 full-building targets [15] with structural/non-structural separation for SCORS [16], and a new Future Homes Standard (FHS) Compliance Checklist [17] supports early-stage regulatory review. By quantifying upfront carbon and linking results to low-carbon and circular material options—including reclaimed content, bio-based choices, and high-recyclability products—the tool functions not only as a carbon calculator but also as a practical enabler of circular, net-zero-aligned design and procurement.

Table 1. Scenarios 1 and 2 materials for the modular Brooklands Building.

Material Type	Material Specification – Scenario 1	Material Specification – Scenario 2
In situ concrete	UK C32/40 (25% GGBS)	UK C32/40 (70% GGBS)
Mortar/screed	1:4 cement:sand mix with average UK cement mix	Gyvlon Binder screed (Anhydritec - UK)
Reinforcement bars	UK (consumption average)	EAF production (Laminés Marchands Européens - France)
Light gauge steel	Frame (Metalperfil, s.a. - Spain)	Horizon Light Gauge Steel Frame (Horizon Offsite Limited - Ireland)
Timber	Softwood (Forest Industries - Ireland)	Softwood (Forest Industries - Ireland)
Light gauge steel	Framing system for Dry Lining (Metsec - UK)	Framing system for Dry Lining (Metsec - UK)
Cavity Barrier	FF102/50 Ventilated Cavity Barrier (Tenmat - UK)	FF102/50 Ventilated Cavity Barrier (Tenmat - UK)
Cement board	BETONYP Cement particle board-(FALCO Zrt - Hungary)	Fermacell H2O Cement board-(Fermacell - Germany)
Plasterboard	Glasroc X sheathing board 12.5mm (Saint Gobain - UK)	Glasroc X sheathing board 12.5mm (Saint Gobain - UK)
Membrane	Vapour Control Layer - Average (A. Proctor Group - UK)	Exoperm Mono SA 250 (Partel - Ireland)
Rockwool	Basic Plus 100mm (Knauf - UK)	Hemp 100mm (IndiNature - UK)
Plasterboard	Gyproc FireLine 15 mm (Saint Gobain - UK)	Gyproc FireLine 15 mm (Saint Gobain - UK)
Membrane	Vapour Control Layer - Average (A. Proctor Group - UK)	Exoperm Mono SA 250 (Partel - Ireland)
Rigid foam	Polyisocyanurate (PIR) 120mm (Kingspan - UK)	Cork 100mm (Amorim - Portugal)
Brick slip	Brick slip 21mm (Vandersanden - Belgium)	K-SLIP 20mm (Kenoteq - UK)
Precast concrete	Concrete Roof Tiles (Marley - UK)	SL8 Roof Tiles (Forticrete Ltd - UK)
Insulated panel system	Trisomet 80mm (Kingspan - UK)	Cork 100mm (Amorim - Portugal)
Plaster skim	Thistle BoardFinish 2mm (Saint-Gobain - UK)	Thistle BoardFinish 2mm (Saint-Gobain - UK)
Sheet	UK Chipboard, import weighted average	Smartply MAX (Smartply - UK)
Membrane	Damp insulation Vi-Pro EPDM (Proventuss Polska - Poland)	Exoperm Mono SA 250 (Partel - Ireland)
Carpet	Eco Compact WT (Ege Carpets - Denmark)	Rocklines carpet tiles (Burmatex - UK)
Internal	FD30 Flush Solid Core Timber Door 2040x926x44mm (Forza - UK)	Moulded panel standard core internal door (JELD-WEN - UK)
External	Steeldor - Steel Personnel Door (Strongdor Limited - UK)	OPUS Wooden Front Doors (Saint-Gobain - Sweden)
Staircase	Timber staircase Amberley (Stairway Joinery Ltd - UK)	Timber staircase Bedminster (Stairway Joinery Ltd - UK)
PVC - Triple glazing	Modular Skylight (triple glazing configuration) (Velux - Denmark)	Modular Designo R6/R8 Skylight triple glazing (Roto - Germany)
PVC - Triple glazing	FIN-Window Nova-line (Finstral SpA - Germany)	FIN-Window Nova-line (Finstral SpA - Germany)
Sealants	SilPruf Joint Sealants (Momentive performance materials - India)	SilPruf Joint Sealants (Momentive performance materials - India)
Waterworks	PVC Rain Gutter System (Plastmo - Denmark)	PVC Rain Gutter System (Plastmo - Denmark)

Using this tool, the environmental performance of the modular Brooklands housing project was assessed. Scenario 1 represents the baseline design, while Scenario

2 introduces targeted material substitutions intended to lower upfront embodied carbon and enhance circularity; the two scenarios are summarised in Table 1. In Scenario 2, conventional higher-carbon products are replaced with low-carbon, bio-based, or more recyclable alternatives, including increased Ground Granulated Blast-furnace Slag (GGBS) content in concrete, the use of anhydrite screed, and the selection of Electric Arc Furnace (EAF)-produced reinforcement steel. Further reductions are achieved by substituting several mineral-based materials—such as PIR insulation, particle boards, and brick slips—with bio-based options, including hemp insulation, cork panels, and brick slips made of near 100% recycled content, while already low-carbon components (e.g., plasterboard, cavity barriers, timber elements) remain unchanged.

4 Analysis and Results

Figure 3 presents the embodied-carbon results for the two scenarios, showing the distribution of emissions across the A0–A5 lifecycle (A0 not shown as it was assumed zero) stages, including embodied carbon, and their comparison against the 2030 upfront-carbon targets [15]. Scenario 2, which incorporates a set of low-carbon construction alternatives, demonstrates a 28% reduction in upfront embodied carbon relative to Scenario 1 and remains comfortably within the 2030 performance threshold. This highlights the considerable carbon-saving potential of substituting conventional materials with lower-impact options at early design stages.

Building on these carbon results, Fig. 4 illustrates the corresponding reusability and recyclability potentials derived from the proposed circularity metrics. The recyclability/reusability potential is defined as the percentage of the building's total embodied carbon that can be potentially recycled/reused at end-of-life. These metrics provide an indicative interpretation of LETI and EU recommendations by assessing whether each material can, in principle, be reused or recycled, and by weighing each material's contribution relative to its embodied-carbon share within the building. Using this method, both scenarios achieve nearly identical circularity outcomes—approximately 72% reusability and 93% recyclability—indicating that the adoption of low-carbon materials does not diminish the building's capacity to retain materials in circulation. Scenario 2 therefore delivers substantial carbon reductions while maintaining the same level of reusability and recyclability as Scenario 1, demonstrating that enhanced circularity and reduced embodied carbon can be achieved simultaneously without performance trade-offs.

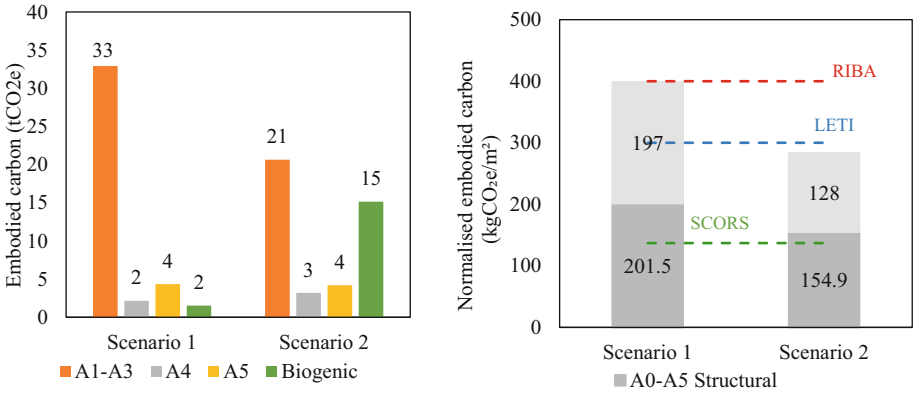


Fig. 3. Estimated embodied carbon (tCO_2e) by lifecycle stages (left) and comparison to 2030 targets ($kgCO_2e/m^2$) (right).

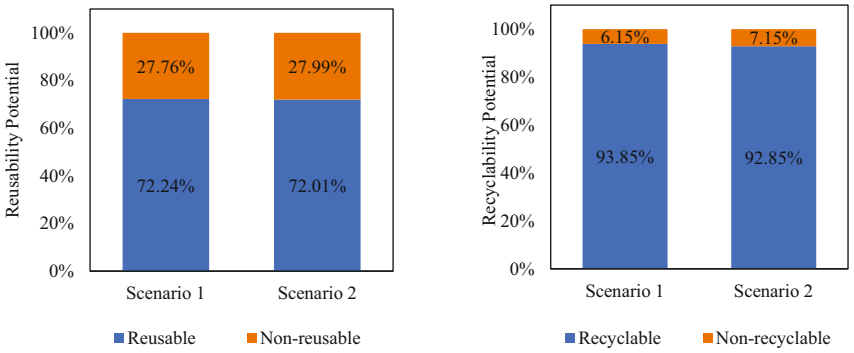


Fig. 4. Reusability (left) and recyclability (right) embodied carbon potential.

5 Conclusions

This study assessed the upfront embodied-carbon and circularity performance of a modular UK dwelling using the enhanced LJMU A0–A5 Upfront Carbon Tool. The scenario analysis showed that targeted material substitutions—such as higher GGBS content, anhydrite screed, EAF-produced steel, and bio-based alternatives—reduced upfront embodied carbon by 28% without affecting circularity, which remained at approximately 72% reusability and 93% recyclability. The circularity metrics used provide indicative alignment with LETI and EU objectives, though actual recyclability varies by product characteristics and available treatment pathways. Standardised recyclability indicators within EPDs, together with stronger domestic recycling infrastructure and clearer frameworks for certifying reusable materials, are needed to support more accurate assessments and wider adoption of circular practices. Overall, the findings demonstrate that modular construction, early material optimisation, and whole-building carbon assessment can jointly advance progress toward 2030 low-carbon and circular-economy targets.

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Axial Global Stability of Corner and Interior Sway Frames in Modular Steel Buildings with Rotary-Type Inter-Module Connections

Kashan Khan[1,2(✉)] and Konstantinos Daniel Tsavdaridis[1]

[1] Department of Engineering, School of Science & Technology, City St George's, University of London, London, UK
Kashan.Khan@citystgeorges.ac.uk
[2] School of Civil Engineering & Architecture, Taizhou University, Taizhou, China

Abstract. Modular steel buildings (MSBs) are increasingly recognised as a sustainable construction solution due to their ability to reduce construction time, material waste, and environmental impact compared with conventional building systems. Their prefabricated nature also supports circular construction through the potential reuse and reconfiguration of modular units and structural components. In such systems, inter-module connections (IMCs) play a critical role in ensuring structural stability, efficient load transfer, and rapid on-site assembly. Rotary-type IMCs are frequently adopted to accommodate construction tolerances, simplify installation, and facilitate efficient modular assembly. However, their influence on the axial global stability of sway frames in MSBs remains insufficiently understood. This study investigates the axial global stability of corner and interior sway frames assembled with rotary-type IMCs through experimental and numerical approaches. Five full-scale sub-assemblage specimens were tested under axial compression to evaluate load–displacement behaviour, failure modes, and stability mechanisms. A finite element model was developed and validated against the experimental results, followed by parametric analyses examining the effects of beam–column stiffness ratio, member gaps, discontinuities, and group configurations on axial capacity. The results indicate that axial instability is mainly governed by lateral sway, second-order effects, and local buckling of upper columns, while rotary-type IMCs effectively transfer forces without premature failure and support efficient modular assembly, enabling demountability and reuse of modular units across multiple lifecycle stages. These findings contribute to design considerations for resilient, reusable, and resource-efficient MSB systems aligned with circular and sustainable construction principles, promoting resource efficiency and lifecycle extension.

Keywords: Modular Steel Buildings · Inter-Module Connections · Axial Compression · Stability Analysis · Sway Frames · Numerical Modelling

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1 Introduction

Modular steel buildings (MSBs) use factory-produced modules that enable rapid assembly, disassembly, and reuse, offering a sustainable construction approach characterised by high prefabrication and reduced material waste, supporting circular construction principles [1]. In this context, design for disassembly is essential to enable lifecycle extension and resource efficiency in the built environment. Conventional welded inter-module connections (IMCs), although structurally efficient, hinder disassembly and limit reuse potential. In contrast, demountable systems such as rotary-type IMCs facilitate rapid assembly and disassembly while maintaining structural integrity, supporting repeated module reuse and reducing construction and demolition waste. In MSBs, IMCs between adjacent modules govern structural stability and load transfer but introduce discontinuities/groupings in structural members, significantly influencing global behaviour. Various IMC systems, including welded, bolted, shear-keyed, pre−/post-tensioned, self-locking, and rotary-type connections, have been investigated under different loading conditions [2–4]. However, unlike conventional steel frames, IMCs often behave as semi-rigid connections, altering stiffness distribution and effective column lengths, making direct application of traditional stability design methods uncertain [5]. Rotary-type IMCs are increasingly adopted due to their demountability, tolerance accommodation, and construction efficiency. Nevertheless, experimental studies on the axial global stability of rotary-connected modular frames under realistic boundary conditions remain limited, with most existing work focusing on grouped columns with idealised fixed conditions [6, 7]. Therefore, this study investigates the axial global stability of corner and interior modular sway frames with rotary-type IMCs through five full-scale experiments and refined finite element (FE) parametric modelling. The findings improve understanding of modular frame behaviour with demountable connections and support the design of reliable, adaptable, and resource-efficient MSB systems aligned with circular construction principles and lifecycle-oriented design strategies.

2 Experimental Investigation of Modular Sway Frames

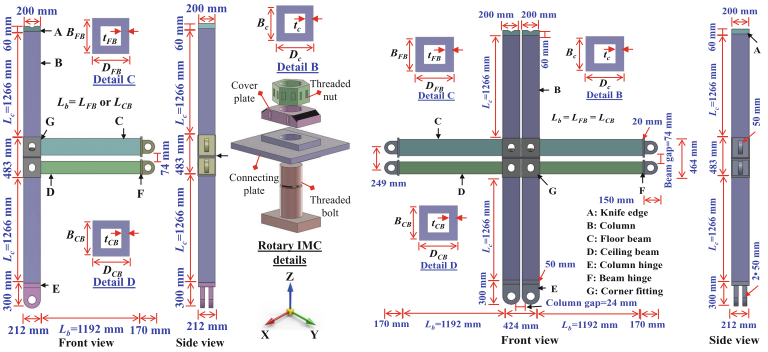
2.1 Specimens and Test Setup

Three corner (RS1–RS3) and two interior (RDD-1 and RDD-2) frame specimens were fabricated using rotary-type IMCs based on a five-storey MSB prototype designed according to GB50017-2017 [8]. The corner frames had a height of 3375 mm and width of 1568 mm, while the interior frames had a width of 3160 mm. Columns were 200 × 200 × 8 mm, while the floor beam (FB) and ceiling beam (CB) had widths of 150 mm with depths of 200 mm and 150 mm, respectively (Table 1). To investigate the influence of the beam–column stiffness ratio, the thickness of the FB and CB was varied (6 mm and 8 mm), as shown in Fig. 1a, b. Material properties were obtained from tensile tests in accordance with GB/T228.1-2010 [9] and used in the subsequent FE modelling. The assembled frames were tested under axial compression applied to the top column using a hydraulic jack with a knife-edge hinge (Fig. 2a, b). A 20% preload was applied for alignment, followed by force-controlled loading to yielding and displacement control to

failure or 85% of ultimate load. Beam-end rollers allowed in-plane rotation and horizontal displacement while restraining out-of-plane movement, thereby simulating realistic sway boundary conditions in MSBs.

Table 1. Design details and capacity of sway modular corner and interior frames

Specimen	Floor beam (mm)	Ceiling beam (mm)	Column (mm)	Capacity (kN)
RS1	150 × 200 × 8 × 1192	150 × 150 × 6 × 1192	200 × 200 × 8 × 1266	1397
RS2	150 × 200 × 8 × 1192	150 × 150 × 8 × 1192	200 × 200 × 8 × 1266	1279
RS3	150 × 200 × 6 × 1192	150 × 150 × 6 × 1192	200 × 200 × 8 × 1266	1244
RDD-1	150 × 200 × 8 × 1192	150 × 150 × 6 × 1192	200 × 200 × 8 × 1266	3793
RDD-2	150 × 200 × 8 × 1192	150 × 150 × 8 × 1192	200 × 200 × 8 × 1266	3646

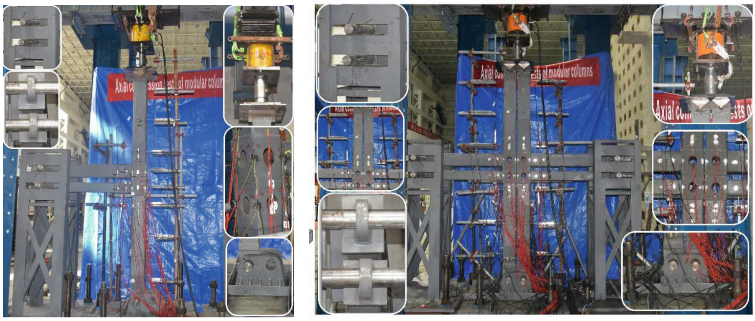


(a) Modular corner frame with rotary IMC (b) Modular interior frame with rotary IMC

Fig. 1. Specimen details of sway steel modular corner and interior frame with rotary IMC

2.2 Failure Modes

All specimens exhibited similar instability mechanisms characterised by in-plane lateral sway, local column buckling, and rotation at the IMCs (Fig. 4 a–e). As axial load increased, horizontal displacements of the FB and CB governed global sway, strongly influenced by the beam–column stiffness ratio. In corner frames, thinner FBs resulted in larger sway responses, whereas thicker beams enhanced stiffness and reduced lateral displacement. At ultimate load, local buckling occurred primarily in the upper columns



(a) Test setup for modular corner frame (b) Test setup for modular interior frame

Fig. 2. General compression testing setup of sub-assembled rotary-connected frames

near the connection zones, typically within 50–200 mm of the column ends, forming a characteristic S-shaped deformation pattern. The lower columns generally remained elastic. Rotary IMCs effectively transferred forces without local failure, maintaining overall structural integrity. Interior frames exhibited similar behaviour; however, specimen RDD-2 showed greater lateral deformation and earlier instability due to its lower beam stiffness compared with RDD-1.

2.3 Load–Displacement Behaviour

All specimens exhibited three response stages: elastic, inelastic, and post-peak softening (Fig. 5 a–e). In the elastic stage, load increased approximately linearly with displacement until yielding. During the inelastic stage, stiffness progressively decreased due to local buckling in the upper columns. Beyond the ultimate load, the response entered a descending branch characterised by increasing sway and rapid strength degradation. Specimens with higher beam stiffness showed greater capacity and initial stiffness, whereas frames with more flexible beams exhibited enhanced ductility and larger post-peak deformation. These results highlight the critical role of the beam–column stiffness ratio and the semi-rigid behaviour of IMCs in governing the global stability and ductility of modular sway frames.

3 Numerical Modelling and Parametric Analysis

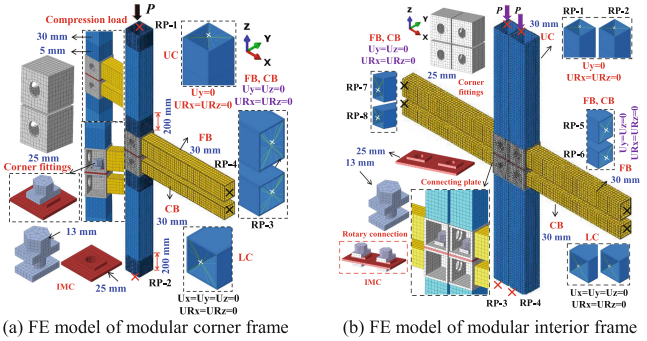
3.1 Finite Element Modelling

A nonlinear FE model was developed in ABAQUS to investigate the stability behaviour of the frames, using C3D8R solid elements with mesh refinement near the column roots (or top) to capture local buckling (Fig. 3 a, b). Linear eigenvalue buckling analysis identified critical modes, followed by nonlinear Riks analysis to simulate post-buckling behaviour. Material properties were derived from tensile tests, assuming Poisson's ratio of 0.3. Boundary and loading conditions were applied using reference points: lower columns permitted in-plane rotation, beams restrained vertical movement, and upper columns allowed both rotation and translation. Beam–column joints were modelled

using tie constraints, while rotary IMCs were defined through surface-to-surface contact with a friction coefficient of 0.3. Initial geometric imperfections, based on the lowest buckling mode, were introduced to capture global sway, local buckling, and second-order effects observed experimentally, with amplitudes taken as $H/600$ or $0.64t_c$ (where H is the specimen height and t_c is the column wall thickness) for local imperfections, and eccentricities of $e = 3.35D_c/7$ (corner) and $e = 3.35D_c/100$ or $7D_c/500$ (inner frame), where e is the eccentricity and D_c is the column cross-section dimension.

3.2 FE Model Validations

The FE model was validated by comparing predicted load–displacement responses and global/local failure modes with experimental results (Figs. 4 a–e and 5 a–e). For RS1–RS3, the average differences were 0.3% in capacity, 9.1% in stiffness, and 8.5% in ductility. For RDD-1 and RDD-2, the predicted values differed from the tests by approximately 1%, 3.2%, and 7.9%, respectively. The model accurately reproduced the observed S-shaped local buckling of upper columns and sway deformation, confirming its capability to capture the mechanical behaviour of modular frames with rotary-type IMCs.



(a) FE model of modular corner frame (b) FE model of modular interior frame

Fig. 3. Verified FE model details of the rotary-connected modular frames

3.3 Parametric Analysis

A parametric study examined the influence of beam and column cross-sectional dimensions, member lengths, connection plate thickness, gaps, and member grouping on frame stability (Fig. 6 a–h). Increasing beam thickness or depth enhanced capacity and stiffness, whereas more flexible beams improved ductility and deformation capacity. Similarly, increasing column size and thickness significantly improved capacity and stiffness by reducing slenderness. In contrast, increasing member length reduced buckling resistance due to higher slenderness, although greater deformation capacity developed prior to failure. Parameters such as beam–column gaps and connection plate thickness had only minor influence. However, increasing the number of columns significantly enhanced load-carrying capacity (up to 482%) and stiffness (approximately 384%) due to load

redistribution, demonstrating a strong grouping effect. Beam–column stiffness ratio, member grouping, and slenderness were identified as the dominant factors governing frame stability, while rotary-type IMCs effectively transferred forces without failure, supporting structural reliability and reusability.

4 Implications for Circular Modular Construction

The results demonstrate that modular sway frames with rotary-type IMCs achieve stable structural performance under compression while enabling demountable and reusable systems. From a circular construction perspective, their ability to facilitate assembly and disassembly without compromising structural integrity offers a clear advantage over conventional welded or grouted connections, which restrict reuse, require additional working space, and often lead to material downcycling at end of life. Rotary IMCs enable modular units to be disassembled, relocated, and reconfigured for multiple use cycles, extending the service life of structural components. This supports design-for-disassembly principles and reduces construction and demolition waste, while improving material efficiency and lowering demand for new structural steel. From a lifecycle perspective, the reusability and adaptability of such systems indicate strong potential for reducing embodied carbon associated with material production and end-of-life processes. Compared with conventional monolithic construction, modular systems with reusable connections can support closed-loop material cycles, retaining components at higher value across multiple reuse stages. The observed structural reliability and absence of premature connection failure confirm that rotary-connected systems are suitable for practical implementation. Their compatibility with rapid assembly, disassembly, and transportation aligns with industrialised construction practices emphasising off-site manufacturing, reduced labour, and increased productivity.

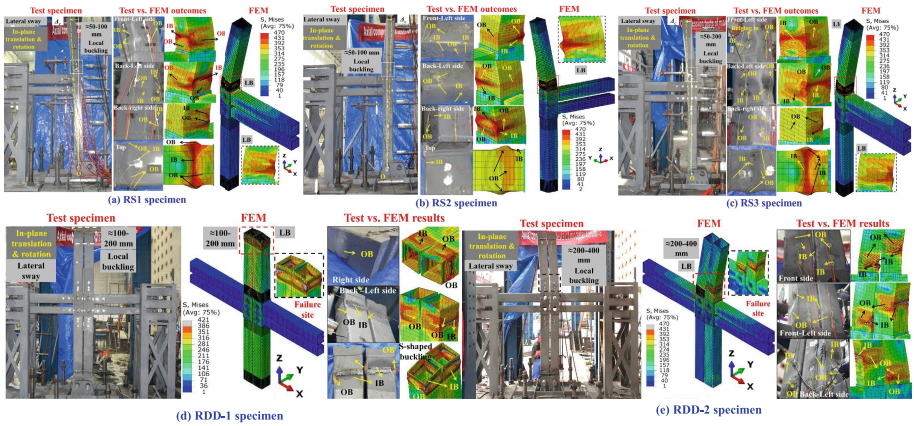


Fig. 4. Comparison of test and FE-predicted failure modes in modular frames

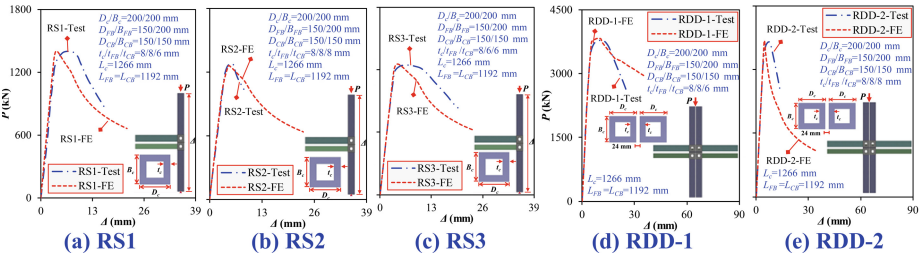


Fig. 5. Comparison of test and FE-predicted load-shortening curves in modular frames

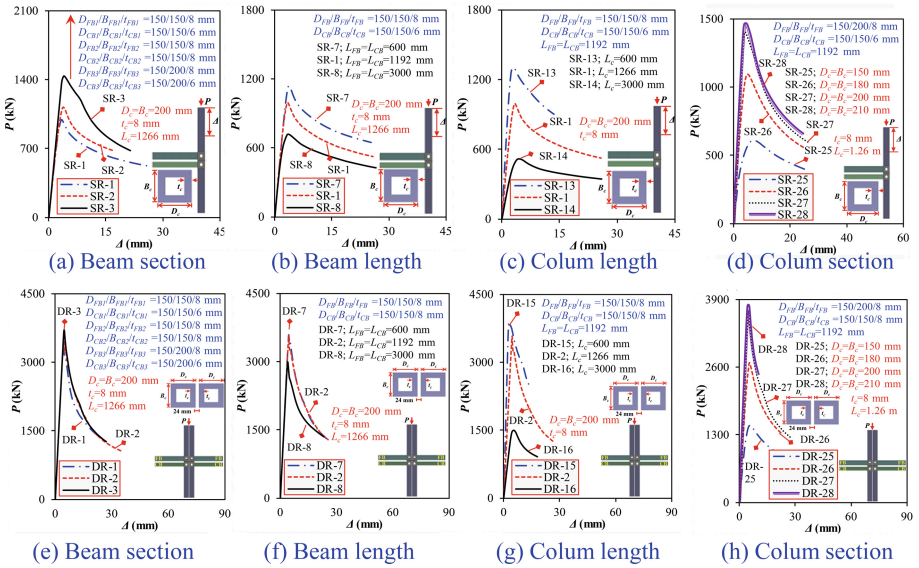


Fig. 6. Parametric study outcomes on the load-shortening curves of modular frames

5 Conclusions

This study investigated the axial global stability of rotary-connected modular corner and interior sway frames through five sub-assemblage experiments and FE parametric modelling. All specimens exhibited typical elastic, inelastic, and post-peak softening responses, with failure governed by in-plane sway instability and local S-shaped buckling of upper columns at the column top or near the IMC regions. The FE model accurately reproduced the experimental responses, including load–displacement behaviour, capacity, stiffness, ductility, and failure modes. Parametric analysis identified the beam–column stiffness ratio, member grouping, and slenderness as the dominant factors influencing stability, while connection plate thickness and module gaps had minor effects. Increasing the number of columns significantly enhanced capacity (up to 482%) and stiffness (approximately 384%) due to load redistribution. Rotary-type IMCs demonstrated

reliable force transfer and structural integrity, enabling demountable and adaptable modular systems. These findings support the development of resource-efficient MSBs with extended service life, aligned with circular construction principles.

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Circular Modular Construction: A Review of Policy, Design, and Reuse Potential in Timber and Steel Systems

Dan-Adrian Corfar[1], Konstantinos Daniel Tsavdaridis[1,2(✉)], and Zhengyao Li[3]

[1] Department of Engineering, School of Science & Technology, City St George's, University of London, London EC1V 0HB, UK
konstantinos.tsavdaridis@city.ac.uk

[2] Institute of Seel Structures, School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou str., Zografou Campus, Athens GR-15780, Greece

[3] Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg 412 96, Sweden

Abstract. Modular construction is increasingly positioned as a pathway to circular economy goals through off-site manufacture, standardisation, and reductions in construction waste. However, these benefits do not necessarily translate into whole life carbon reductions for timber and steel modular building systems, where site waste forms a limited share of embodied emissions. This paper examines whether modular construction can support higher value circular strategies, specifically adaptability, deconstruction, and reuse at both module and sub assembly levels, rather than relying on waste minimisation claims alone. It combines a concise review of timber and steel volumetric modular systems with practitioner survey evidence, focusing on design approaches and connection strategies that influence disassembly and reuse. The results indicate that multi-cycle reuse is technically feasible when systems are explicitly designed for reuse, although current evidence more often reflects intended reuse or technical potential than verified repeated redeployment in practice. Prevailing industry practices such as irreversible interfaces, tightly integrated building services, and limited documentation continue to constrain adaptability and recovery in mainstream projects. The review also suggests that circular modular construction is unlikely to follow a single reuse model across all sectors, and that hybrid approaches may often be more realistic than full module redeployment in permanent applications. Across both materials, the enabling conditions that would enable modular reuse at scale are reversible joints, standardised interfaces, and digital documentation that supports traceability and consistent assessment.

Keywords: Circular Modular Construction · Design-for-Deconstruction · Design-for-Reuse · Timber Modular Buildings · Steel Modular Buildings

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1 Introduction

Modular construction is increasingly presented as a pathway to circular economy goals in the built environment because off-site manufacture, standardisation, and controlled production can reduce construction waste and improve delivery efficiency [1–4]. However, these advantages do not necessarily translate into meaningful whole-life carbon reductions for timber and steel modular building systems, where site waste represents only a limited share of embodied emissions [5]. This raises a more important question than waste minimisation alone, namely whether modular systems can support higher-value circularity such as adaptability, deconstruction, and reuse.

This paper examines circular modular construction through a concise review of policy and design themes supported by practitioner survey evidence. It focuses on timber and steel volumetric modular systems, since both are widely associated with circularity but present different technical and practical constraints for reuse. Particular attention is given to demountable connections, standardised interfaces, and digital documentation, as these influence whether modules and sub-assemblies can be disassembled, reassessed, and redeployed in practice. The paper therefore considers not whether modular construction is circular in principle, but under what conditions it can support credible multi-cycle reuse.

2 Circularity, Demountability, and Reuse in Modular Systems

2.1 Regulatory Context

Current policy and industry guidance increasingly frame circularity in construction in terms of whole-life carbon, adaptability, durability, reuse, and traceability rather than waste diversion alone. This is reflected in recent European and UK frameworks, including the Circular Economy Action Plan, the recast Energy Performance of Buildings Directive, PAS 2080, and the UKGBC Whole Life Carbon Roadmap, all of which place emphasis on retaining material value through longer service life, recovery, and reuse [6–9]. Within this context, modular construction is often presented as a favourable delivery model because standardisation, off-site manufacture, and kit-of-parts logic may support disassembly and future redeployment. However, the policy direction does not imply that modular construction is circular by default. For both timber and steel modular systems, the relevance of modularity to circular construction depends on whether systems are designed and documented in a way that supports adaptability, disassembly, and reuse across more than one life cycle.

2.2 Demountability and Reuse in Timber and Steel Modular Systems

At system level, the circular potential of modular construction depends on whether buildings, modules, or sub-assemblies can be disassembled and reused without disproportionate technical, logistical, or regulatory difficulty. In timber modular systems, this potential is evident across several project types, but case studies also show that intended reuse through relocation is not always realised. Volumetric timber projects such as

PLACE/Ladywell and Y:Cube (London, UK) were both conceived around demountable modular housing, yet their reuse trajectories remain shaped by condition, regulation, and redeployment constraints. Other projects, including HASLE TRE (Oslo, Norway) and Krokodil (Winterthur, Switzerland), embed circularity more explicitly through demountable timber connections and design strategies intended to support future recovery, even where second-life reuse has not yet been demonstrated. Evidence from reusable panelised systems further shows that timber demountability depends not only on structural concept, but also on controlled disassembly, grading, storage, transport, and the ability to adapt future design to recovered material [10–12].

Steel modular systems present a somewhat different picture because repeated redeployment is already more established in parts of practice, particularly in relocatable buildings and commercial modular supply chains. Demonstrator projects such as the Legacy Living Lab and M-Box 1.0, as well as supplier-based systems such as Portakabin and Algeco, show that repeated relocation is feasible when module typology, lifting strategy, and service integration are compatible with reuse. However, system-level reuse remains constrained by factors beyond the primary structure, including cavity barriers, integrated services, acoustic and fire layers, tolerance accumulation, and the effort required to reassess recovered modules [13–16].

Across both timber and steel systems, demountability is therefore shaped not only by the structural frame, but by the extent to which the wider building system supports separation, handling, reconfiguration, and future compliance. The case evidence is uneven and often reflects intended or potential reuse rather than verified multi-cycle redeployment, so a distinction is needed between nominal demountability, recovery after a single disassembly event, and verified reuse across repeated cycles. Verified redeployment is more evident in portable and relocatable sectors than in permanent modular schemes, where service integration, procurement, financing, and long-term occupation create different constraints.

2.3 Connection-Level Demountability in Timber and Steel Modular Systems

While system strategy determines the overall possibility of reuse, practical demountability is governed to a large extent by connection design. In timber modular systems, connection detailing strongly affects whether structural elements can be separated without local damage that reduces reuse potential. Reviews of reversible timber connections show that dry mechanical systems are generally more compatible with adaptability, disassembly, and reuse than adhesive or heavily invasive fixing methods, particularly where inelastic demand can be concentrated in replaceable steel components rather than in the timber itself [17, 18]. This direction is illustrated in Fig. 1, where Fig. 1a shows a practical dry timber connection designed for reversible assembly, while Fig. 1b shows the MOD-IT connection, which more explicitly addresses disassembly and reuse at the interface level.

In steel modular systems, a similar distinction arises between connections developed primarily for erection efficiency and those developed with demountability and repeated use more directly in mind. Inter-module connections for hot-rolled steel modular buildings include a wide range of mechanical, interlocking, and hybrid arrangements, but their design is often governed by alignment, force transfer, and assembly requirements in first

use rather than by multi-cycle reuse [19]. This contrast is reflected in Fig. 2, where Fig. 2a shows a practical steel inter-module connection for modular assembly, while Fig. 2b shows the interlocking concept proposed by Corfar and Tsavdaridis [20], developed more directly around demountability and reuse. For both materials, the comparison highlights that connection design determines whether modules and sub-assemblies can be dismantled, inspected, and redeployed with acceptable effort and damage.

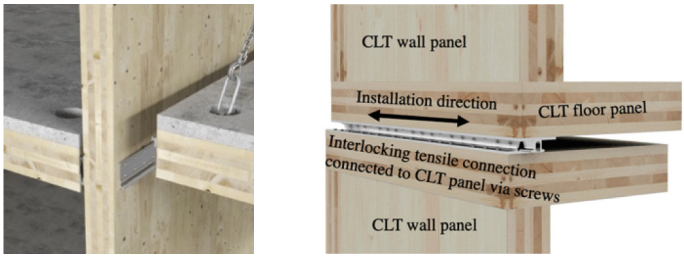


Fig. 1. Examples of demountable timber connection systems: (a) Rothoblaas LOCK FLOOR connector [19] and (b) MOD-IT connection [18].

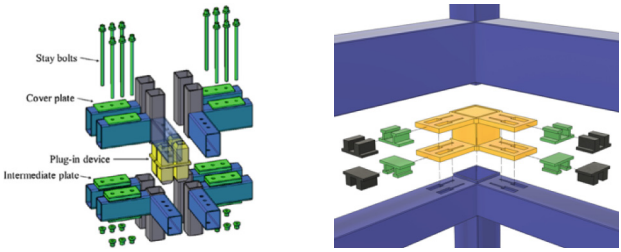


Fig. 2. Examples of demountable steel inter-module connection systems: (a) plug-in bolted connection and (b) interlocking connection [21].

3 Questionnaire Survey Method

To complement the review, an international questionnaire survey was conducted to capture practitioner perspectives on modular construction in relation to circularity, with particular attention to barriers, reuse pathways, and enabling measures. The questionnaire was developed by the authors, refined through internal review, and administered online between September and November 2025 using purposive sampling through professional networks and project partners. A total of 33 respondents participated, including structural engineers, architects, manufacturers, contractors, researchers, and clients from

the UK, Northern Europe, Italy, Canada, and Australia. The survey combined closed-ended questions, including Likert-scale and multiple-choice items, with optional open-text responses addressing industry attitudes, barriers to adoption, adaptability, reuse, disassembly of different connection types, and the adequacy of current standards and documentation approaches. Results are reported using descriptive statistics and thematic reading of open comments. Given the modest sample size, the survey is treated as exploratory and indicative rather than statistically generalisable and is used to triangulate themes identified in the literature.

4 Survey Findings and Discussion

Within the survey sample, practitioner responses indicate that modular construction is generally viewed positively and is strongly associated with circular economy objectives, particularly adaptability, ease of deconstruction, and reuse. However, respondents linked circular value not to off-site manufacture alone, but to whether systems can be disassembled, reconfigured, and redeployed in practice. As shown in Fig. 3, respondents rated modular construction as highly relevant to adaptability, deconstruction, and reuse, indicating that these higher-value circular strategies are already central to how modularity is understood in practice.

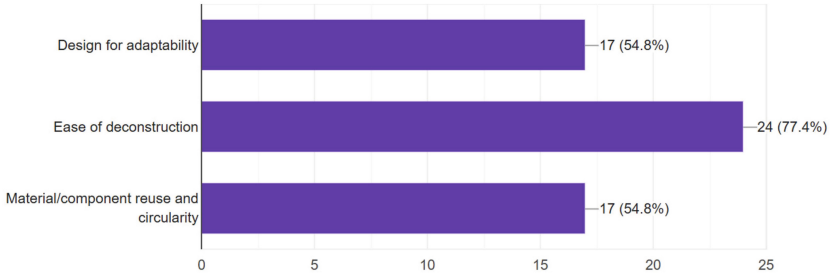


Fig. 3. Practitioner appraisal of the relevance of modular construction to (1) design for adaptability, (2) ease of deconstruction, and (3) material or component reuse and circularity.

The survey also shows that the main barriers to circular modular construction are not only technical. Respondents most frequently identified lack of standardisation, high initial cost, regulatory and approval challenges, and market perception or customer acceptance. This suggests that even where modular systems are physically recoverable, reuse may remain limited if there is no clear pathway for assessment, compliance, and acceptance in subsequent applications.

The survey also highlighted the importance of connection design as a technical issue. Respondents viewed bolted steel connections more consistently favourably in relation to disassembly, with responses clustered toward the lower end of the difficulty scale, whereas timber connections using steel plate interfaces were also viewed relatively favourably but with a broader spread of responses. As shown in Fig. 4 a, b, bolted steel connections were more clearly associated with lower perceived disassembly difficulty,

while timber connections using steel plate interfaces received a more mixed, though still generally favourable, assessment. This is consistent with the review evidence, which indicates that practical reuse depends on whether interfaces allow controlled disassembly, limited local damage, and subsequent reassessment.

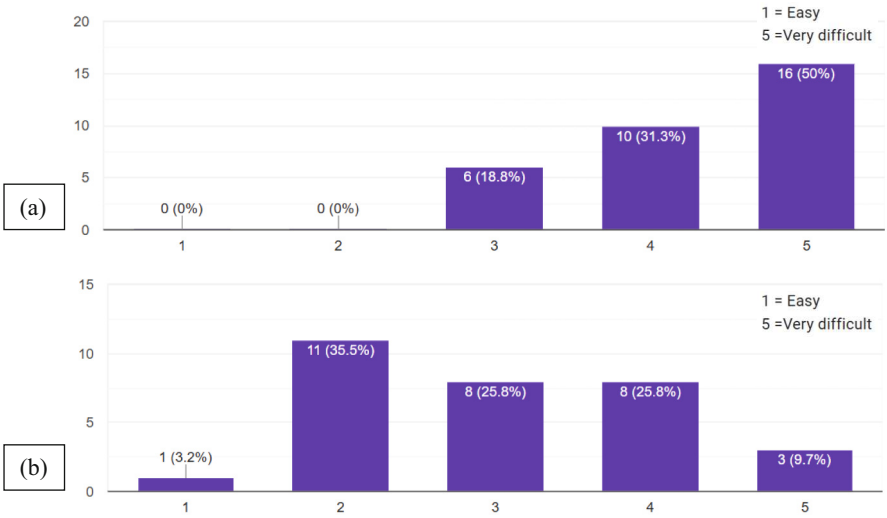


Fig. 4. Practitioner appraisal of the perceived disassembly difficulty of selected connection types in modular systems: (a) bolted steel connections and (b) timber connections using steel plate interfaces.

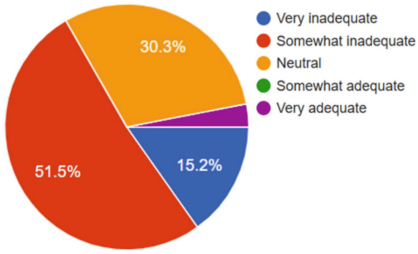


Fig. 5. Practitioner appraisal of the perceived adequacy of current design codes and guidelines in addressing modular construction and connection design.

A final theme concerns standards, guidance, and digital documentation. Respondents expressed limited confidence that current codes and guidelines adequately address modular construction and connection design in relation to circularity, as shown in Fig. 5. They also placed high value on digital documentation, particularly product or module passports, standardised structural assessment procedures, deconstruction manuals, and as-built BIM information. The survey therefore indicates that reuse at scale depends not

only on reversible technical design, but also on traceability, assessment protocols, and clearer approval routes.

5 Conclusions

This paper examined circular modular construction through a concise review of policy and design issues supported by practitioner survey evidence focused on timber and steel modular systems. The results indicate that modular construction is viewed as relevant to circular economy goals but also show that modularity alone is insufficient to deliver higher-value circular outcomes. Across both the review and the survey, circularity was shown to depend less on waste reduction than on whether systems are designed and documented to support adaptability, disassembly, reassessment, and potential reuse across multiple life cycles.

The reviewed evidence also suggest that circular modular construction is unlikely to follow a single reuse model across all sectors. In traditional permanent modular applications, demountability may remain central, but higher-value reuse may depend less on relocating whole modules (for social mobility and economic reasons) than on enabling adaptation, reconfiguration, and flexibility over time. Hybrid (combined) approaches may therefore be more realistic than assuming full module redeployment for all modular systems.

In both timber and steel modular systems, this depends strongly on connection strategy and interface design. Reversible joints, accessible detailing, and standardised interfaces are therefore central conditions for practical reuse. At the same time, the survey shows that the barriers to circular modularity are not only structural or material related. Practitioners identified standardisation gaps, regulatory uncertainty, and limited documentation for reuse as major constraints, while digital product or module passports, standardised reassessment procedures, and clearer approval workflows were consistently identified as important enablers.

Overall, circular modular construction should be understood as a design, documentation, and governance-dependent pathway rather than as an automatic consequence of off-site manufacture. The key issue is no longer whether modular systems can support reuse in principle, but how to make reuse reliable in practice. Future work should develop frameworks to assess damage, material degradation, overall condition, and thus reuse potential across repeated disassembly and redeployment cycles.

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Scaling Structural Steel Reuse in the UK: Evidence from 35 Projects (2022–2025)

Assel Katenbayeva[1](✉) and Konstantinos Daniel Tsavdaridis[2,3,4]

[1] Alliance for Sustainable Building Products, Bognor Regis PO22 9SL, UK
asselia@asbp.org.uk
[2] City St George's, University of London, London EC1V 0HB, UK
[3] Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou str., Zografou Campus, Athens GR-15780, Greece
[4] Efestos Hub, Goswell Road, London EC1V 0HB, UK

Abstract. Reusing structural steel can deliver substantial embodied carbon savings (up to 98% versus "new" steel, and 88% vs. recycled), yet barriers remain to scaling. The UK provides an early policy-led signal, with reuse concentrated in London commercial developments where circular economy statements and pre-demolition audits are required for referable planning applications. This paper synthesises 4 years of industry-embedded research across six Innovate UK-funded projects: over 60 semi-structured interviews, nine supply chain site visits spanning production, stockholding/processing, fabrication, construction, and demolition, and a database of 35 UK steel reuse projects delivered in 2022–2025 (15 analysed in depth). UK practice is predominantly member-level reuse (beams and columns) rather than whole-frame relocation, increasing the need for early identification, matching, verification, and logistics. Evidence from the project database (21/35 projects in London; 16/35 commercial) and stakeholder accounts points to three recurring constraints: (1) high-stakes selection decisions under uncertainty in member condition and provenance; (2) limited visibility of forthcoming donor buildings and weak mechanisms to share reuse-relevant information across organisations; (3) misaligned end-of-life incentives, with demolition contractors carrying programme and liability risks while receiving limited incentives for recovered material; and (4) commercial sensitivity to steel price volatility. The paper identifies a focused set of scale-up interventions: strengthening selection capability for donor buildings and members, improving donor-building visibility and traceability infrastructure, aligning incentives through procurement and fiscal mechanisms, and recognising donor-side recovery through clearer reporting and reward structures. These findings provide practical insights for scaling circular steel markets.

Keywords: Structural Steel Reuse · Circular Steel · Circular Construction · Deconstruction · Urban Mining

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1 Introduction

Steel reuse avoids remelting, retains component value, and can deliver substantial embodied carbon savings [1]. The UK is currently the leading market for structural steel reuse, with a large number of implemented projects and an expanding body of industry guidance, and provides an informative early market for understanding how reuse can move from isolated pilots towards repeatable practice, particularly in commercial developments in large cities where planning requirements and whole-life carbon narratives have created a clearer demand signal [2]. Yet uptake remains uneven and difficult to scale, particularly where donor-side recovery is commercially risky and where information on forthcoming donor buildings and reusable inventories is limited [1, 3–5].

Drawing on 4 years of industry-embedded research across six Innovate UK-funded projects (DISRUPT [1], DISRUPT II [6], ARMOUR [7], E-TRACS [8], RE-CELL [9], and HARNESS [10]), we synthesise evidence from 60+ interviews, nine site visits, and a database of 35 UK steel reuse projects delivered in 2022–2025, including 15 analysed in depth [1, 6, 11].

Three questions are addressed:

RQ1: What characterises the UK steel reuse market in 2022–2025?
RQ2: What constraints limit scaling-up?
RQ3: What interventions are most plausible for unlocking bottlenecks?

The paper contributes an empirical profile of recent UK activity, evidence on how policy, incentives, and information shape donor-side supply, and a focused set of scale-up interventions grounded in current delivery conditions.

2 Background

In the UK, around 50,000 buildings are demolished annually [12], releasing large volumes of high-quality structural steel. Most of these (93%) are routed to recycling rather than reuse [13]. At the same time, around 80% of UK scrap is exported for processing overseas, reflecting constraints in domestic recycling capacity [14]. Based on published A1–A3 EPDs and benchmark data, reusable steel is reported as 69.5 $kgCO_2e/t$ [15], compared with 560 $kgCO_2e/t$ for recycled structural steel sections [16], and 1,850 $kgCO_2e/t$ for global average primary steel [17], highlighting the substantial embodied-carbon advantage of reuse. Reuse, therefore, offers both embodied carbon reduction and domestic material value retention.

Previous UK-focused work shows that the main barriers to structural steel reuse are systemic rather than purely technical. Reported constraints include cost, availability and storage, limited client demand, traceability, and supply chain gaps and lack of integration. The latter relates to incentives and coordination: unless there is visible demand and a clear financial upside, there is limited motivation to invest in the additional capability required for deconstruction, storage, and testing/verification, so reuse remains opportunistic rather than routine [3]. Another study [4] analysed how cost and risk are distributed across the UK construction value chain, noting that viability depends strongly on where marginal costs sit and who carries programme exposure. Key issues include the additional labour

and time associated with deconstruction and reconditioning (relative to demolition and new fabrication), as well as opportunity costs under tight fabrication programmes. The study highlights the value of intermediaries (for example, specialised stockists) that can take on sourcing, storage, reconditioning, and assurance, thereby reducing transaction costs and perceived risk for design and delivery teams. More recent synthesis work frames barriers at the ecosystem level, including limited material availability from demolition, challenges in maximising reusable outputs, gaps in design rules and standards, and high upfront costs. It also draws attention to decision-critical early choices (whether to deconstruct, what to target, and what evidence to capture) because these shape the downstream burden of testing, reconditioning, and redesign [5]. Given the rapid recent market development, updated evidence from delivered projects is needed.

3 Methodology

This study adopted an embedded qualitative research design, combining longitudinal engagement across applied research projects with interviews, site observations, and structured project documentation. This multi-method qualitative approach enabled triangulation between practitioner perspectives, observed practices, and evidence from implemented projects to detect patterns shaping the emerging steel-reuse market.

Interviews (n = 60+). Semi-structured interviews were conducted over 4 years across the steel reuse value chain. Participants included developers, structural engineers, architects, main contractors, steel contractors/fabricators, steel stockholders, demolition contractors, and pre-demolition auditors. Interviews explored decision drivers and criteria, practical constraints and opportunities, approaches used to manage verification and risk, and perceived intervention needs.

Site visits (n = 9). Site visits were undertaken to observe practices and operational constraints in context. These included demolition or deconstruction sites (2), fabrication facilities (3), steel stockholding and processing yards (2), and construction sites incorporating reused structural steel (2). Observations focused on decision points, logistical constraints, and information handovers between actors.

Project database (n = 35). A structured database of UK projects delivered between 2022 and 2025 with reclaimed structural steel was compiled. Inclusion criteria were: (i) projects located in the UK; (ii) reuse involving the removal and reuse of structural steel members (excluding adaptive reuse or retention in situ); and (iii) verification through public documentation and/or stakeholder confirmation. For 15 in-depth case studies, additional information on drivers, procurement routes, challenges, and lessons learned was triangulated through interviews and documentary sources [1, 6, 11].

Data analysis. Interview transcripts, case study notes, and site observations were analysed using thematic analysis. The material was systematically reviewed and categorised into key themes, including drivers of reuse, procurement models and risk allocation, information and traceability, cost and price sensitivity, and potential intervention mechanisms. Case studies were analysed using a structured template capturing procurement routes, relationships between donor and recipient buildings, reuse types, verification approaches, constraints, and lessons learned. Findings were refined through cross-case comparison and triangulation (validating observations and opinions) between interviews, site observations, and documentary evidence.

4 Findings and Discussion

4.1 Market Evolution, Profile, and Procurement Models

UK experience indicates a shift from earlier portal frame relocation in industrial buildings towards member-level reuse within commercial sector. Earlier documented activity (2004–2014) involved relocating whole frames or large assemblies, where matching and verification were comparatively straightforward [4]. Since 2022, projects have involved the reuse of individual beams and columns in new structures. This is more demanding because viability depends on early member selection, timely design matching, and decisions under uncertainty around coatings, damages, usable lengths, attachments, and provenance. London's policy context has been important in shaping this shift. Circular Economy Statements and stronger expectations for pre-demolition audits have helped to drive reuse consideration in major commercial schemes and encouraged the earlier generation of reuse-relevant information [2]. However, these demand-side signals alone do not mobilise donor-side supply.

Table 1 summarises UK projects with steel reuse completed in 2022–2025 (noting that projects to be completed in 2026 are excluded). Across the current dataset of 35 projects, reuse activity is concentrated in London (21/35) and in commercial developments (15/35), followed by industrial projects (8/35), 5 art/public realm, 4 residential, and 2 bridges. Industrial projects are more regionally distributed and mostly involve reclaimed tubulars reused as piling or foundation elements. Reuse of tubulars for piling has been established for some time, whereas reuse in commercial building projects has only gained momentum since 2022.

Reuse is predominantly member-level rather than whole-frame, increasing reliance on early identification of reusable members in donor buildings, matching to recipient design and programme, and verification pathways where provenance is uncertain.

Five procurement models were identified. In stockholder-driven open-market reuse, stockholders source, process, and sell recovered steel, broadening access but often increasing uncertainty around provenance and reconditioning scope. In client-driven portfolio reuse, a developer retains steel from a donor asset for use in a new project, simplifying provenance and verification but limiting wider market pooling. Hybrid procurement combines a known donor asset with reclaimed stock sourced from the market. Two further models were observed: demolition-contractor-led reuse, in which contractors recover steel for sale into reuse markets rather than scrap, and fabricator-led reuse, in which surplus or unused sections are retained for future use, typically with reconditioning and testing undertaken by specialist intermediaries. This latter model is not reported in Table 1, as although the steel was reclaimed, it has not been reported as reused, i.e. incorporated into a new structure. This suggests that a wider set of actors is beginning to capture value from reclaimed steel.

Within commercial projects, stockholder-led reuse (7 projects) and hybrid procurement (5 projects) dominate, with fewer pure client-led examples (2 projects). However, project counts alone may not reflect the scale of reuse. Hybrid projects often rely primarily on steel sourced from the client's own portfolio, supplemented by smaller quantities from stockholders. For example, at 30 Duke Street, the largest steel reuse commercial

Table 1. Summary of UK structural steel reuse projects (2022–2025).

#	Project	Year	City	Tonnes	Type	Proc.*
1	The Entopia Building	2022	Cambridge	4	COM	S
2	Holbein Gardens	2022	London	25	COM	C + S
3	Domestic retrofit project	2022	Lichfield	1	RES	S
4	The Tree of Trees sculpture	2022	London	NR	ART	S
5	Public Park (former Victorian viaduct)	2022	Manchester	NR	ART	NR
6	Reuse of tubulars as piling at Brent Cross West Thameslink Station	2022	London	NR	IND	S
7	Reuse of tubulars as piling at Waterfront Plaza	2022	Stoke-on-Trent	NR	RES	S
8	Bedfont Lakes	2023	London	10	COM	C
9	Brent Cross Town Substation	2023	London	33	IND	S
10	Langley Business Centre	2023	Slough	NR	IND	D
11	22 Baker Street	2023	London	NR	COM	C
12	Sloane Square House	2024	London	21	COM	S
13	Tower Bridge	2024	London	16	COM	C + S
14	6 St Andrew Street	2024	London	24	COM	S
15	Tan House Footbridge	2024	Wokingham	14	BR	S
16	Reclaimed steel tubulars used as guided augerbore	2024	NR (non-London)	NR	IND	S
17	Reuse of the portal frame	2024	NR (non-London)	NR	IND	S
18	Temporary bridge for the North Yorkshire Council	2024	Arkle Town	NR	BR	S
19	55 Great Suffolk Street	2024	London	20	COM	C + S
20	Portal Frame (Data Centre)	2024	South Wales	600	IND	D
21	Bristol Zoo Project	2025	Bristol	30	COM	S
22	Whale on the Wharf sculpture	2025	London	NR	ART	S
23	Week at the Knees sculpture	2025	London	NR	ART	S
24	Chelsea Garden sculpture	2025	London	NR	ART	S
25	1 Golden Lane	2025	London	40	COM	D
26	Timber Square	2025	London	108	COM	S
27	Domestic retrofit project	2025	London	NR	RES	D
28	30 Duke Street	2025	London	440	COM	C + S

(*continued*)

Table 1. (*continued*)

#	Project	Year	City	Tonnes	Type	Proc.*
29	Appledore Clean Maritime Innovation Centre	2025	Bideford	NR	IND	S
30	Steel Tubular Piling for Glasgow Airport Fire Mains	2025	Glasgow	NR	IND	S
31	334 Oxford Street	2025	London	NR	COM	NR
32	76 Southbank	2025	London	24	COM	S
33	Cambridge House, 90–93 Piccadilly	2025	London	75	COM	C + S
34	20 Finsbury Dials	2025	London	99	COM	S
35	Social Housing Scheme	2025	Yorkshire	161	RES	S

Note: *Proc. = Procurement model; NR = not reported; Type – COM = commercial, RES = residential, ART = art/sculpture, IND = industrial, BR = bridge; Procurement – S = direct supply, C = contractor-led, D = developer/client-led, U = unknown; C+S = hybrid.

project as of March 2026, most of the steel was reused from the client's portfolio, with only a smaller proportion sourced from stockholders.

4.2 Constraints and Scale-Up Priorities

Compared with earlier UK literature, some enabling conditions have improved. Interviewees reported greater awareness, stronger familiarity with design approaches, and the role of stockholders, capable of sourcing, storing, reprocessing, and managing testing of reclaimed steel. Storage remains a practical issue, but it is increasingly managed within stockholder yards and, in some demolition-led and fabricator-led cases, within existing operational space.

Four constraints nevertheless remain influential. First, demand is stronger but localised – London's planning regime provides a clearer compliance and reporting context, while incentives outside London yet remain weaker and less consistent. Second, donor-side incentives remain weak – demolition contractors face additional planning, handling, sequencing, and perceived liability risks when recovering steel for reuse, while carbon and circularity credit is captured in the recipient project narrative. Third, information gaps persist; limited visibility of forthcoming donor buildings and inconsistent member-level information increase the cost and uncertainty of verification and reconditioning. Fourth, reuse economics remain highly sensitive to steel price volatility and to uncertainty in member condition and reprocessing.

These findings suggest that scaling depends on improving the conditions for predictable delivery. Four priorities emerge. First, member- and building-level selection capability should be strengthened, because coatings, attachments, composite interfaces, connection details, and usable length directly affect reconditioning scope, testing needs, and programme risk. Second, donor-building visibility and interoperable information infrastructure should be improved by linking pre-demolition audits to standardised

member inventories and design requirements. Third, incentives should be better aligned through procurement and fiscal mechanisms, particularly where public procurement can create steadier demand. Fourth, donor-side recovery should be explicitly recognised through clearer reporting of recovered tonnes and routes to reuse, alongside contractual or fiscal mechanisms that reward deconstruction effort.

5 Conclusions

This paper provides an empirical profile of the UK structural steel reuse market in 2022–2025. Recent activity is dominated by member-level reuse in London commercial developments, reflecting stronger policy signals and carbon reporting requirements, but also increasing reliance on early selection, verification, and logistics. Market awareness and intermediary capability have improved, yet scaling remains limited by weak donor-side incentives, persistent information gaps, and cost sensitivity. To move from repeatable pilots to a broader circular steel market, interventions should focus on stronger selection capability, better donor-building information, more effective procurement and fiscal incentives, as well as clearer recognition of donor-side recovery. These lessons offer useful insights for other markets with structural steel reuse activity.

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Evaluation of Initial Imperfections in Deconstructed Steel Elements for Structural Reuse in Secondary Life Cycles

Adrian Ciutina(✉), Viktor Szalai, Aurel Stratan, and Viorel Ungureanu

Politehnica University of Timişoara, Timişoara 300006, Romania
adrian.ciutina@upt.ro

Abstract. Within the broader framework of the circular economy and sustainable construction practices, the reuse of structural components or systems offers a promising strategy for reducing the carbon footprint of new buildings. To enable the integration of existing elements into subsequent life cycles, it is essential to assess their condition and structural performance at the end of their initial service life. For trusses made from structural hollow-sections the reuse pathways could consider the use of the original truss or through cutting and subsequent welding of truss elements. Regardless of the chosen approach, a detailed evaluation of geometric imperfections accumulated during the first life cycle is required to ensure safe and reliable reuse. The study examines geometric imperfections in RHS steel truss members in two conditions: (1) immediately after fabrication, representing the baseline state, prior to the first service life and (2) after a first life cycle involving loading histories representative of serviceability and ultimate limit states from dead and snow loads. The tested elements correspond to top-chord members under eccentric compression, scaled for laboratory constraints. Imperfections were quantified using industrial laser scanning and dedicated processing software, enabling high-resolution assessment of geometric deviations. The measured values were compared with standard tolerance limits to evaluate compliance and detect potential degradation. Particular attention is given to the residual imperfections over the service life, as these may affect structural reliability for reuse.

Keywords: Truss Elements · Imperfections · Reuse · Tolerances

1 Constrains and Challenges in Reuse of Steel Elements

One of the main advantages of steel structural systems is their capacity to be reintegrated into new buildings at the end-of-life cycle. The residual value of steel becomes thus an important advantage as this reduces the ecological footprint of manufacturing compared to producing "virgin" steel. However, the reuse process bypasses the energy-intensive processes of recycling (by shredding, melting, and reforming) steel as shown by Yeung et al. [1]. While recycling plays a significant role in reducing the demand for primary raw materials, the direct reuse of steel components represents a substantially more effective strategy for lowering the environmental impact and conserving material and energy

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resources. Currently, only about 11% of steel in Europe is reused, whereas approximately 88% undergo recycling [2]. Empirical assessments indicate that the reuse of steel elements can reduce environmental impacts by up to 95% compared with the production of new steel, underscoring its relevance for circular economic practices and sustainable construction [3]. However, in the process of deconstruction for reuse, several barriers could be encountered, as mentioned by Bartsch [4], such as material quality, integration in new design projects, lack of costumer interest or important costs for reconstruction.

Among the barriers to reusing steel elements, the importance of member imperfections could be considered as a challenge as these could affect the further reuse of elements, especially if stability of elements is among the design criteria of elements. The structural and geometrical imperfections could arise in manufacturing of the structure, its assembly and during the use of the structure. As shown by Smak and Straka, various reasons could lead to increased imperfections during the life cycle of structures, such as removal of elements or manufacturing [5]. Radwan and Kövesdi [6] proposed special buckling reduction factors for reclaimed steel members considering the increased imperfections accumulated during service life.

2 Experimental Tests

Fundamentally, the typical reuse of truss structures could be done in two ways: (i) either by the reuse of the entire truss roof structure or (ii) by reclaiming of individual elements by considering the structural disassembly and re-fabrication in new truss or individual members. While the first option is restricted by geometric limitation in transportation and careful disassembly of the full structure, the second possibility should integrate the cut-and-refabrication methodology. As shown by Brutting et al. [7], the re-fabricated elements could be re-integrated in new original truss members, steel masts or secondary structural members, such as purlins or girts in new buildings.

However, the new buildings should fulfil the actual normative conditions including strength, stiffness, material requirements and imperfections. If the firsts are common for usual design, the evaluation of imperfections should be carefully made as the elements could possess increased imperfections from previous life-cycle.

2.1 Selection of Testing Specimens

The study focuses on analysing a top-chord member from an industrial truss beam originally designed with a 30 m span and a 6 m bay, subjected to eccentric compression as described in [8], and subsequently scaled for laboratory testing. The scaling process preserved key similarity parameters, including the buckling resistance ratio, the width-to-thickness (c/t) ratio, and the non-dimensional slenderness, ensuring consistency between the original and scaled sections. Thus, the original top-chord member RHS200 $\times$ 120 $\times$ 80 of a 4 m length was scaled- down for laboratory testing RHS100 $\times$ 60 $\times$ 4 (S500) and a length of 1.5 m.

Ten testing specimens were conceived for testing as shown in Table 1 from which two were tested to buckling failure (MC-A-F), four to serviceability loading conditions

(MC-A-SLS) and the other four (MC-A-ULS) to ultimate loading conditions. The serviceability and ultimate limit state conditions were simulated using a hypothetical cyclic loading protocol. In the first stage, the permanent load (G_k) was applied, followed by a second stage involving progressively increasing cyclic loads to represent the design snow load (S_k) according to serviceability and respectively ultimate limit states acting on the truss structure [8].

Table 1. Description of MC-A experimental specimens.

Type of test	Specimen label	Type of load	Loading protocol	No. of specimens
Members in eccentric compression RHS 100 × 60 × 4	MC-A-SLS	SLS loading	Cyclic	4
	MC-A-ULS	ULS loading	Cyclic	4
	MC-A-F	Failure	Monotonic	2
	MC-A-SLS-F*	Failure after SLS	Monotonic	2
	MC-A-ULS-F*	Failure after ULS	Monotonic	2

*selected from the MC-A-SLS/ULS specimens, after initial SLS/ULS testing

2.2 Test Set-Up

Figure 1 shows the test set-up, which consists of specimens fixed at their ends by two pinned supports into a universal testing machine that applied the load in load control for SLS and ULS loading and displacement control specimens tested to for failure. The applied eccentricity was of 22.68 mm, in order to produce the similar moment to the non-scaled element (having an eccentricity of 58.22 mm).

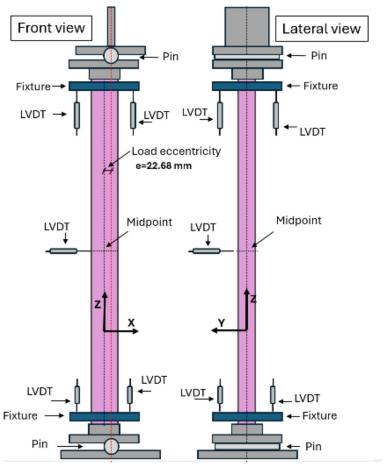


Fig. 1. Testing set-up for eccentric MC-A specimens.

To record deformations during testing, ten displacement transducers were used: eight LVDTs measured axial deformations and end rotations, while two additional LVDTs monitored mid-section deformation along the major axes.

2.3 Experimental Results: Cyclic Loading

Figure 2 presents the recorded transversal deformations for specimens MC-A-SLS-04 and MC-A-ULS-04, loaded in cyclic SLS and respectively ULS conditions.

As expected, for both specimens, the in-plane deformations (X-axis) are greater than the out-of-plane (Y axis) deformations due to the imposed axial eccentricity. For in-plane deformations, the maximum transient (7.2 mm) and the residual (2 mm) transversal deformations are more important in case of ULS loading than the values recorded in SLS conditions of 2.8 and 0.1 mm respectively. The recorded values show that a residual imperfection is recorded after loading.

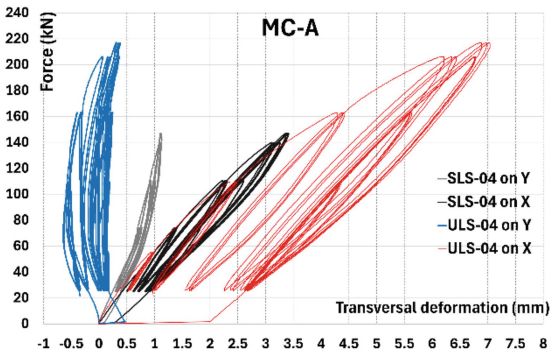


Fig. 2. Force – lateral deformation of the central cross-section response curves for specimens MC-A-SLS-04 and MC-A-ULS-04 under cyclic SLS/ULS loading.

3 Evaluation of Imperfections for RHS Truss Elements

Table 2. Values of initial and residual member imperfections after SLS/ULS tests.

Specimen	Initial imp. on *Y* (mm)	Residual imp. on *Y* (mm)	Initial imp. on *X* (mm)	Residual imp. on *X* (mm)
MC-A-F-01	0.059	–	0.053	–
MC-A-F-02	0.151	–	0.076	–
Average (F)	**0.105**	–	**0.065**	–
MC-A-SLS-01	0.173	0.250	0.023	0.335
MC-A-SLS-02	0.157	0.189	0.020	0.456

(*continued*)

Table 2. (*continued*)

Specimen	Initial imp. on Y (mm)	Residual imp. on Y (mm)	Initial imp. on X (mm)	Residual imp. on X (mm)
MC-A-SLS-03	0.105	0.183	0.009	0.508
MC-A-SLS-04	0.158	0.622	0.010	0.482
Average (SLS)	**0.148**	**0.311**	**0.016**	**0.445**
MC-A-ULS-01	0.088	0.446	0.023	1.417
MC-A-ULS-02	0.102	0.668	0.098	1.302
MC-A-ULS-03	0.103	0.433	0.077	1.442
MC-A-ULS-04	0.109	0.687	0.043	1.476
Average (ULS)	**0.101**	**0.559**	**0.060**	**1.409**

To capture the exact outer geometry of the elements, blue-ray laser scans were performed before and after cyclic testing. The resulting surface maps represented total imperfections, combining both local effects – such as thickness variations and surface waviness – and global member imperfections. Member imperfections were extracted by fitting a second-order polynomial to the measured surface profile, constrained to pass through the centroids of the end cross-sections and some nine equally spaced intermediate centroids as explained elsewhere [8]. Imperfections were evaluated along the two principal axes, X (in-plane) and Y (out-of-plane).

The full scanning of the elements can offer a difference between the local (sectional) and member imperfections. However, generally, the local imperfections can influence both the shape and magnitude of the resulting member imperfections.

Table 2 presents the values of maximum member (bow) imperfections obtained from scanning of specimens before and after cyclic loading at SLS/SLU conditions.

3.1 Initial Imperfections

Figure 3 shows as example the measured initial total imperfections for specimen MC-A-SLS-02 on X and Y axes, as well as the bow (member) imperfections obtained by polynomial fitting. The values are within the allowable tolerances specified in EN 1090-2:2008 [9] of 6 mm or $L/750$ (here 2 mm) for truss members. As observed in Table 2 similar values were obtained for all tested specimens. Considering the measured specimens, it can be observed that the largest initial imperfections are recorded in the direction of the weakest cross-section dimension (Y axis or out-of-plane direction).

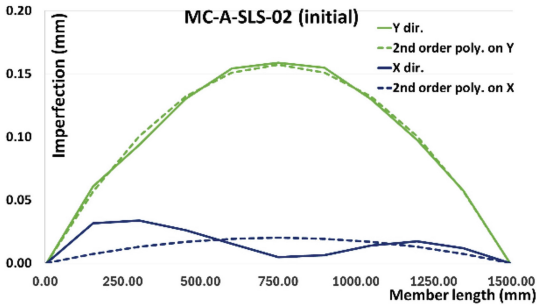


Fig. 3. Initial imperfections for MC-A-SLS-02 specimen.

3.2 Increased Imperfections After SLS/SLU Loading

Figure 4 shows the equivalent total in-plane (*X* axis) residual imperfections resulted on MC-A specimens after cyclic SLS (left) /ULS (right) conditions, in comparison to the initial imperfections. For both loading conditions, the residual imperfections after loading are much larger than the initial imperfections, as shown also in Table 2:

– average values of imperfections: 0.016 mm initial/0.445 mm after SLS loading;
– average values of imperfections: 0.006 mm initial/1.409 mm after ULS loading.

It could be mentioned that increased imperfections were recorded also in the Y direction (along the weaker cross-section dimension), but the differences are smaller. The obtained values are consistent with the recorded residual imperfections presented in Sect. 2.3.

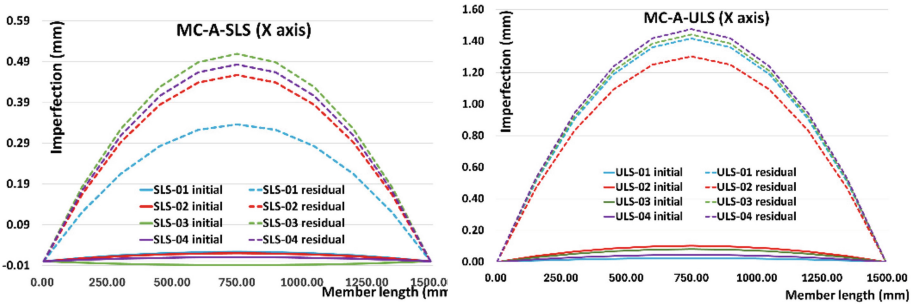


Fig. 4. Initial vs. increased residual total member imperfections after cyclic SLS/SLU loading.

4 Influence of Imperfections at Ultimate Loading

Figure 5 shows the resulting force – transversal deformation for the specimens loaded to failure: two virgin specimens (F-01 and F-02), two after SLS loading (SLS-01-F and SLS-01-F) and respectively two after ULS loading (SLU-01-F and SLU-01-F). Table 3

presents the synthetic values recorded during testing, as the maximum load, deformation at maximum load and axial shortening as well as the imperfections at the starting of loading.

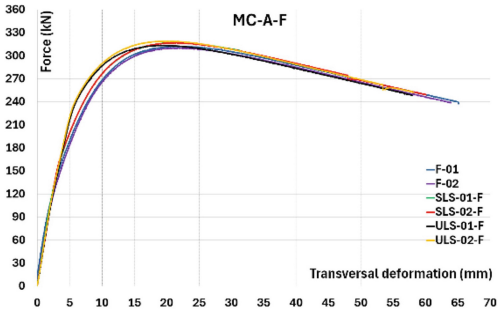


Fig. 5. Force – transversal deformation curves for MC-A-F specimens.

The specimens exhibit comparable responses, with similar maximum loads (F_{max}) and only minor amplitude variations of about 2.2%. The deformations recorded at F_{max} are within a narrow range of 20–23 mm. Comparable initial stiffness and stiffness in the unloading branches are observed as well. However, the ULS specimens display a noticeably stiffer behaviour in the pre-peak region up to F_{max}. The axial shortening recorded during loading is a direct consequence of the buckling deformation of the specimens.

Table 3. Synthetic values resulted from failure tests.

Specimen	Axial shortening (mm)	Maximum load F_{max} (kN)	Deformation at F_{max} Y axis (mm)	Initial imp. Y axis (mm)
MC-A-F-01	3.12	312.95	21.28	0.059
MC-A-F-02	2.71	310.22	22.89	0.151
MC-A-SLS-01-F	2.87	316.76	21.08	0.335
MC-A-SLS-02-F	3.12	317.35	20.86	0.456
MC-A-ULS-01-F	2.80	313.64	19.73	1.417
MC-A-ULS-02-F	2.89	319.72	20.25	1.302

All specimens failed by flexural buckling about the major inertial axis (X-axis), as illustrated in Fig. 6. This failure mode is consistent with the applied eccentricity. In a few specimens, however, minor deformations were also observed about the minor axis (Y-axis). The recorded results indicate that no intuitive correlation exists between the maximum forces achieved during testing and the initial geometric imperfections measured before the application of the failure load. This suggests a key conclusion: for RHS elements subjected to eccentric compression, the ultimate failure behaviour is

not significantly influenced by initial imperfections, provided these remain within the allowable limits prescribed by design standards.

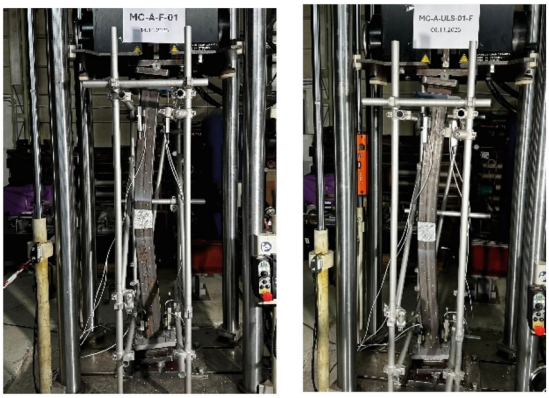


Fig. 6. Failure by lateral flexural buckling of F-01 and ULS-01-F specimens.

5 Conclusions

The paper investigates the influence of geometric imperfections in reclaimed RHS steel truss elements subjected to eccentric axial loading, representing typical SLS and ULS life-cycle conditions with consideration for future reuse. Imperfections were quantified through 3D scanning of the specimens before and after testing Their significance was assessed by correlating the measurements with the ultimate load-bearing performance of the elements.

The geometric scans revealed that the total initial imperfections of the specimens were minimal, with average deviations of 0.12 mm about the minor inertial axis—substantially below the normative limit of 2 mm. Under eccentric axial compression, the mid-length transient deformations increased from roughly 3.2 mm (0.2% of the element length) under SLS loading conditions to 7.2 mm (0.48%) under ULS loading. A similar trend was observed for the residual member imperfections, idealized as a polynomial: mean values increased from 0.445 mm for SLS to 1.445 mm for ULS loading conditions.

Both the initial imperfections and the residual imperfections measured after SLS and ULS loading remained within the allowable limits prescribed by current design standards. Consequently, the reclaimed RHS elements satisfy the geometric criteria for reuse in a subsequent service life. Moreover, the experimental results indicate that the ultimate failure behaviour of RHS members subjected to eccentric compression is not significantly affected by prior SLS or ULS loading.

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Sustainable Buildings, Infrastructures and Cities: Sustainability Assessment Frameworks, Sustainable Design, Construction, Operation and Management; Synergies Across Scales

Advancing Regenerative and Circular Building Practices in Kosovo: Pathways to Net-Zero and Low-Carbon Urban Development

Bahri Prebreza(✉)

University of Prishtina, Prishtina, Kosovo
bahri.prebreza@uni-pr.edu

Abstract. The transformation of Kosovo's built environment toward a regenerative and circular model represents an urgent step in aligning national development with European sustainability frameworks. The country's building sector, characterized by outdated construction practices, low energy efficiency, and limited integration of renewable energy, contributes significantly to greenhouse gas emissions and resource inefficiency. This study aims to explore transformative pathways for achieving net-zero and carbon-neutral buildings in Kosovo, emphasizing systemic change across design, policy, and practice.

This research adopts a qualitative policy-analysis and comparative literature review approach, supported by synthesis of secondary quantitative energy performance data derived from existing studies, institutional reports, and national energy strategies.

The study proposes a framework for accelerating the circular transition of Kosovo's building sector through three core strategies: mainstreaming renewable energy technologies in urban planning, promoting adaptive reuse and energy-retrofitting of existing buildings, and establishing participatory governance models that integrate scientific, industrial, and community expertise.

The research highlights Kosovo's potential to contribute meaningfully to a regenerative and low-carbon built environment in Southeast Europe.

Keywords: Circular Economy · Net-Zero Buildings · Renewable Energy Integration · Regenerative Architecture · Energy Efficiency · Sustainable Urban Development

1 Introduction

Kosovo's transition toward a regenerative and circular built environment is increasingly recognized as a strategic priority for aligning national development with European sustainability agendas and climate commitments. The building sector in Kosovo remains one of the largest consumers of energy and a significant contributor to greenhouse gas emissions, largely due to aging building stock, insufficient thermal insulation, inefficient heating systems, and the continued reliance on fossil-fuel-based electricity. In addition, conventional linear construction practices - characterized by high material consumption, limited recycling, and short building life cycles - further intensify environmental pressures and resource depletion.

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Recent European policy frameworks, including the EU Green Deal, the Energy Performance of Buildings Directive (EPBD) recast, and circular economy action plans, provide a reference model for transforming the built environment toward climate neutrality. For Kosovo, adopting similar principles requires a systemic shift that integrates energy efficiency, renewable energy technologies, and circular material flows throughout the entire building life cycle - from design and construction to operation, renovation, and end-of-life recovery. The building sector plays a crucial role in global efforts to mitigate climate change and improve energy sustainability. Buildings account for nearly 40% of global energy consumption and approximately 36% of energy-related greenhouse gas emissions, making them one of the most critical sectors for decarbonization strategies. Similar trends are evident in Southeast Europe, including Kosovo. The majority of the building stock was constructed during periods when energy performance standards were minimal or nonexistent. Consequently, many residential and public buildings suffer from poor insulation, inefficient heating systems, and outdated construction materials [1].

Kosovo faces major challenges in achieving a sustainable energy future while addressing climate change and reducing carbon emissions. With its current reliance on lignite, the country must shift toward renewable sources like solar, wind, hydropower and other renewable sources [2].

Recent studies highlight the critical role of the building sector in Kosovo's energy and climate transition. According to a national energy efficiency assessment supported by the World Bank [1], buildings account for approximately 47–48% of Kosovo's final energy consumption, making them the largest energy-consuming sector in the country. In addition, the total building stock is estimated at around 45 million m^2 of floor area, of which nearly 75% consists of residential buildings, reflecting the dominance of household energy demand in the overall energy system [3]. Energy intensity in Kosovo's residential sector is estimated at about 278 kWh/m^2 per year, significantly higher than the EU average and approximately 25% above the Western Balkan average, largely due to inadequate insulation, inefficient heating systems, and outdated construction practices [4, 8].

Energy efficiency interventions in public buildings alone could achieve 30–50% reductions in energy consumption, demonstrating the large impact of building retrofits and technological upgrades [5, 9]. At the same time, Kosovo's energy system remains heavily dependent on fossil fuels, with roughly 90% of energy production derived from fossil sources, which significantly increases the carbon intensity of buildings that rely on grid electricity for heating and cooling.

Research analyzing apartment blocks in Kosovo demonstrates that optimal combinations of retrofit measures can significantly reduce heating energy consumption while lowering environmental impacts [6]. Another important aspect of sustainable building development involves passive architectural design strategies. Research on natural ventilation in Kosovo demonstrates that passive cooling and ventilation techniques can significantly reduce electricity consumption in buildings while improving indoor comfort [7].

2 Kosovo's Current Energy Landscape

Kosovo's energy sector relies heavily on lignite, which causes significant pollution and emissions. Its aging coal plants, Kosovo A and B, are inefficient and contribute to unreliable power supply, resulting in frequent shortages and imports. (see Table 1.) Renewables like hydropower, wind, and solar remain limited, though expansion efforts are in progress. The Energy Strategy of the Republic of Kosovo 2022–2031 is a key policy document that outlines Kosovo's vision for a sustainable, secure, and integrated energy sector. Key reforms include alignment with the EU Clean Energy Package, the Energy Efficiency Directive, and climate-related frameworks. The Strategy also supports the National Energy and Climate Plan (NECP) and Kosovo's commitments under the Sofia Declaration to achieve carbon neutrality by 2050 [2].

Table 1. Capacity mix in Kosovo, 2021. (Source: Energy Strategy of the Republic of Kosovo 2022–2031)

Fuel	Name	Year of commissioning	Installed capacity, MW	Available capacity, MW
Lignite	Kosovo A3	1970	200	135
	Kosovo A4	1971	200	135
	Kosovo A5	1975	210	135
	Kosovo B1	1983	339	260
	Kosovo B2	1984	339	260
Wind	–	–	137	–
Hydro	–	–	110–132	–
PV	–	–	10	–
Biomass	–	–	1.2	–
Total:	–	–	**1546–1568**	–

Larger investments are needed, alongside efforts to address high energy use in homes and industry caused by poor insulation and inefficient heating.

3 Methodology

This research adopts a mixed-methods approach that combines qualitative and quantitative analysis. The methodology consists of three main components: **1. Policy analysis:** Evaluation of national energy strategies, climate policies, and building regulations relevant to energy efficiency and renewable energy integration; **2. Literature-based energy performance modeling:** Analysis of published research examining building energy consumption, retrofit strategies, and emission reduction potential and **3. Stakeholder and institutional analysis:** Review of existing reports and studies assessing barriers to implementation, including financial constraints, institutional fragmentation, and technological limitations.

This multidisciplinary approach enables the identification of both technical solutions and governance challenges affecting the transformation of Kosovo's building sector.

4 Energy Consumption in Kosovo's Building Sector, Energy Efficiency Potential and Emerging Opportunities

The study identifies three interconnected dimensions shaping Kosovo's transition toward regenerative and circular buildings: technological, regulatory, and socio-economic drivers. The proposed framework is not presented as a predictive engineering model, but as a strategic analytical framework derived from comparative policy analysis and synthesis of existing empirical studies. This framework links renewable energy integration, energy retrofitting, governance coordination, and circular construction principles into a coherent transition pathway for Kosovo's built environment.

By combining these drivers, the framework connects design innovation, technological solutions, and policy measures to enable systemic change in Kosovo's building sector. The ultimate goal is to reduce operational energy demand, lower greenhouse gas emissions, enhance resource efficiency, and create a regenerative built environment that is resilient, sustainable, and aligned with European climate and sustainability objectives: **1. Technological drivers** that include building-integrated photovoltaics; High-performance thermal insulation materials; Heat pumps and efficient HVAC systems; Smart energy management systems; Building energy modelling and digital monitoring technologies. **2. Regulatory drivers** that include energy performance of buildings directive alignment; National energy efficiency regulations; Building energy certification schemes; Financial incentives for renewable energy and building renovation; Carbon reduction targets and climate policies and **3. Socio-economic drivers** that include investment mechanisms and green financing; Capacity building for architects, engineers, and construction professionals; Public awareness on energy-efficient buildings; Energy cost reduction for households, and job creation in the green construction sector.

Existing research confirms that buildings dominate Kosovo's energy demand. In addition to high energy consumption, Kosovo's energy system is still largely dependent on fossil fuels, particularly lignite-based electricity generation. Consequently, reducing building energy demand would significantly decrease greenhouse gas emissions and improve energy security.

Figure 1 illustrates the electricity demand and supply in Kosovo. The data indicates a steady increase in energy demand over the past decade, reflecting economic development, urbanization, and growth in the building sector. This trend highlights the urgent need for improving energy efficiency in buildings and integrating renewable energy technologies. Reducing energy demand in the built environment is therefore a critical step toward achieving net-zero and carbon-neutral buildings in Kosovo.

Studies consistently indicate substantial opportunities for improving building energy performance. The results suggest that energy-efficiency measures could reduce building energy demand by approximately 44%.

These savings could be achieved through a combination of strategies including: thermal insulation upgrades; energy-efficient windows and building envelopes; heat pumps and advanced HVAC systems and integration of solar photovoltaic systems.

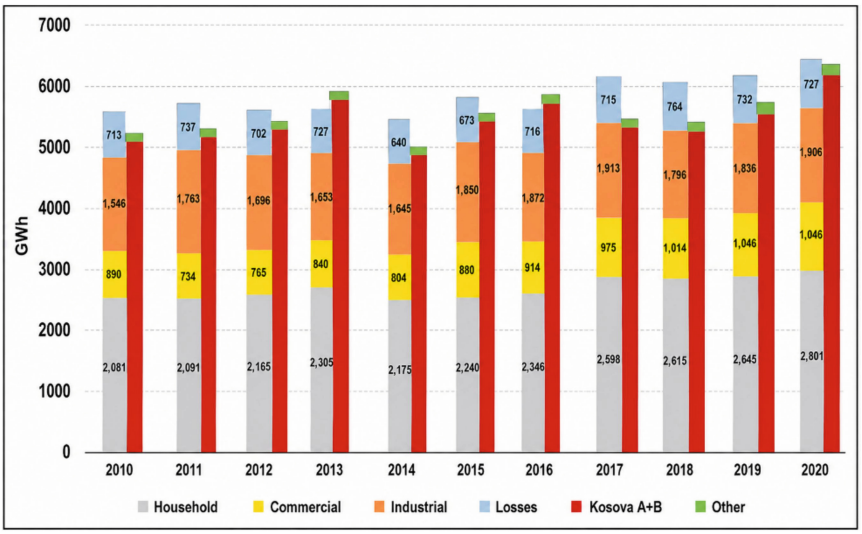


Fig. 1. Elements of electricity demand and supply, 2010–2020, GWh (Source: KOSTT, ERO)

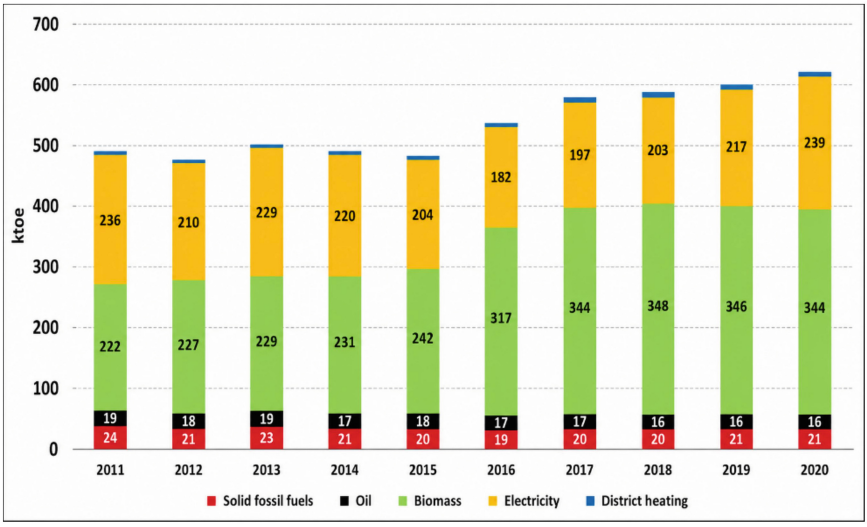


Fig. 2. Energy consumption in the household sector, ktoe (Source: Eurostat)

In Kosovo, demand for electricity varies by month, and in several categories this difference is quite significant. Household consumption is highest during the winter season, largely due to use of electricity for space heating. Recently, the Kosovo power system has faced significant pressure due to the increase in electricity demand resulting in the

need for expensive imports of electricity, especially during the heating season (October–March), when many household customers switched to heating their homes with electricity, instead of using the more expensive wood pellets (Fig. 2).

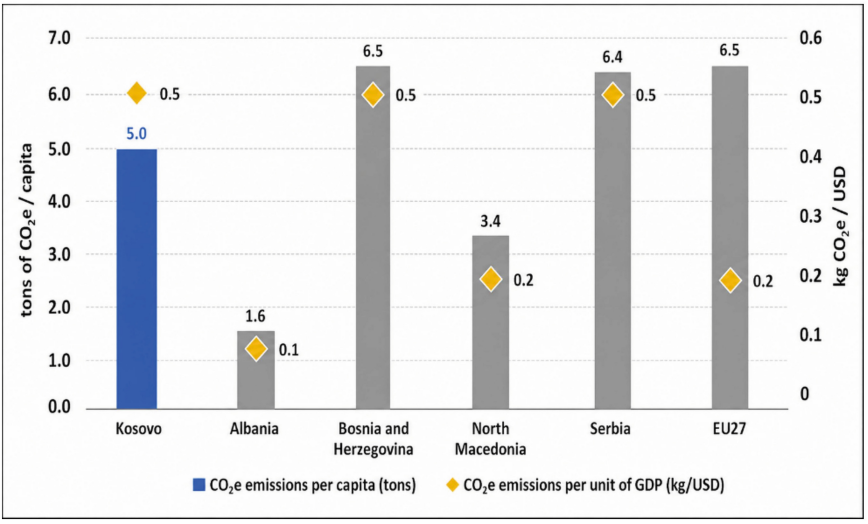


Fig. 3. GHG intensity and GHG emissions per capita in the region (Source: Kosovo Environment 2020 Report of environmental indicators)

According to the latest greenhouse gas (GHG) inventory of Kosovo, annual emissions amounted to 9.613 million tons CO_2eq in 2019. The share of fuel combustion was 86%, to which the power and heating sectors contributed with 66% (6.316 million CO_2eq). Whereas pollution from transport and heating is distributed across the country, the power sector's impact is concentrated in one area (in and around the capital, Prishtina). The overall emission trend shows some fluctuation, but the level has not changed significantly over the years for which data are available, ranging between 8.8 and 10.5 million tons CO_2eq. As shown in Fig. 3. the per capita emissions were below the EU average in 2019, but the GHG emission intensity of the economy is more than twice as much as the EU average.

The forecast of economic growth (GDP) is an important factor for the forecast of electricity demand in Kosovo. Table 2 presents the indicators of development of GDP based on the Economic Reforms Program of the Government of the Republic of Kosovo.

Energy efficiency policies are distributed across multiple governmental institutions, which often leads to **Coordination difficulties**; **Limited financial incentives** that include high upfront costs of building renovation and renewable energy systems discourage widespread adoption and **Lack of stakeholder collaboration** that include insufficient collaboration between academia, industry, and government institutions that slows innovation and knowledge transfer.

Despite these challenges, several initiatives demonstrate the potential for sustainable transformation. Examples include: pilot solar photovoltaic installations in public

Table 2. Projections of economic growth according to the document (Source: The Economic Reforms Program).

GDP real growth	2020–2028
Low scenario	2.2%
Baseline scenario	4.3%
High scenario	5.4%

buildings; municipal climate and green action plans and international energy-efficiency programs funded by development institutions. These initiatives indicate a growing awareness of sustainability issues and provide a foundation for further policy and technological development.

5 Pathways Toward Regenerative and Circular Buildings

Circular economy principles in construction involve recycling building materials, designing for disassembly, and promoting resource-efficient construction techniques. In the Kosovo context, opportunities also exist for revitalizing traditional materials and techniques such as local stone construction, timber elements, lime-based finishes, and adaptive reuse of masonry structures. These practices can reduce embodied carbon, support local supply chains, and preserve regional architectural identity while con-tributing to a modern circular economy.

6 Conclusion

The transformation of Kosovo's building sector represents a critical component of the country's transition toward a sustainable and low-carbon economy. Buildings account for a significant share of national energy consumption and greenhouse gas emissions, making them a priority for climate mitigation efforts.

The findings of this study demonstrate that substantial improvements in energy efficiency and carbon reduction can be achieved through integrated approaches combining technological innovation, policy reform, and stakeholder collaboration. By implementing strategies such as renewable energy integration, building retrofitting, and participatory governance, Kosovo can move toward a regenerative and circular built environment aligned with European sustainability objectives.

Furthermore, achieving a sustainable transformation of Kosovo's built environment requires stronger institutional coordination and long-term investment frameworks. Policy instruments that support large-scale building renovation, renewable energy integration, and energy-efficient urban planning will be essential to accelerate decarbonization in the building sector. In particular, targeted financial incentives, green financing mechanisms, and regulatory alignment with European energy and climate policies can stimulate both public and private investments in sustainable construction practices.

Strengthening collaboration between universities, research institutions, industry stakeholders, and public authorities will be crucial for advancing innovation and knowledge transfer. Such collaborative efforts can help position Kosovo as an emerging contributor to sustainable and regenerative urban development in Southeast Europe.

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A House for the Body

Miguel Veríssimo(✉)

Solar Trap – Architecture, Porto, Portugal
solartrap.arch@gmail.com

Abstract. In the transition from linear Cartesian models to systemic regenerative thinking, humanity is increasingly contextualized within "A Web of Life". In this paradigm, where the shelter constitutes a technological externalization of the human niche, buildings operate as primitive somatic extensions governed by identical physical and biological laws; their organization mirrors the functional logic of human physiology and global ecological constraints. Because humans evolved to prioritize competitive survival via ecosystem modification rather than steady-state sustainability, modern buildings function as metabolic mediators that physically manifest our contemporary evolutionary mismatch. By processing multi-scalar flows of energy, mass, and information—from the individual to the biosphere—buildings primitive-grade analogues of human anatomy, physiology, and homeostatic feedback loops, either exacerbating biospheric entropy through open-loop resource depletion or operating as active thermodynamic nodes within an interconnected reality. Although the house is the primary mediator of human adaptation, architectural treatises neglect the complexity of the building's biological essence reducing the BODY<>HOUSE<>NATURE triad to mere anthropometric, ergonomic, or cultural abstractions. This reductionism overlooks our bodies as active biological, psychological, and social agents whose metabolic needs act as catalysts for technological evolution and ecosystem service appropriation. Addressing this conceptual neglect, the study 'A HOME FOR THE BODY' reframes the house not as an industrial product or a 'machine for living,' but as a complex bio-entity intrinsically linked to human anatomical, physiological, metabolic, and neurological functions. Grounded in recent advances in systems biology, this research proposes a framework based on dissipative, low-entropy processes to reformulate BODY<>HOUSE interfaces across nested scales - from cellular tissues to the biosphere - utilizing systemic design-thinking to reshape habitats by mimicking life's low-impact principles."

Keywords: Body-House · Bio-Architecture · Systems-Thinking · Architecture-Physiology · Body-Thermodynamics

1 From Mechanistic Architecture to Bio-design Thinking

"While a house is an extension of the body, and the body a biological organism, the relationship between the human body and built environments has been framed-especially since the Industrial Revolution-by a reductionist Cartesian pragmatism, that separated

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in architecture, as in other disciplines, the logics of biological systems from intellectual and scientific production, elevating an anthropocentric view of Humans<>Nature relationship. Within this mechanical framework, architecture optimized mass production to accommodate urban population surges, forcing the body—our primary perceptual interface—to adapt to rigid industrial constraints. This linear path-dependency is historically understandable given capital-intensive life-cycles, yet it reveals an evolutionary mismatch: our opportunistic 'Stone Age hardware' used industrial technology to amplify ancestral instincts of resource dominance, scarcity consumption, and hyperbolic discounting ('now' bias), rather than managing abstract, slow-moving threats like climate change or the "tragedy of the commons" . This paradigm, epitomized by Le Corbusier's technocratic metaphor of the 'house as a machine for living,' reduced human activity to measurable anthropometric and ergonomic parameters, instrumentalizing the body while ignoring its physiological, metabolic, and neurological biocomplexity. However, contemporary systems ecology—rooted in Ludwig von Bertalanffy's Systems Theory, Fritjof Capra's web of life, and Gregory Bateson's relational cognition—challenges this view. Intertwined with Alan Turing's morphogenesis and Maturana and Varela's autopoiesis, living systems are redefined as self-producing, open thermodynamic networks. Similarly, Victor Olgyay's bioclimatic principles and Luis Fernández-Galiano's energy histories proved that buildings are dynamic thermal couplers, a relational understanding reinforced by James J. Gibson's ecological psychology and Paul Rodaway's multisensory geographies. As Manuel Damásio notes, consciousness transforms humans into active agents of homeostatic control. Guided by culture—acting as an ethical software update to override biological shortsightedness and redefine social prestige away from extraction—the home transcends its industrial definition to become a bio-entity: an exosomatic prosthesis following Georgescu-Roegen in 1971, and extended nervous system where technology like - sensors, AI, mobile phones, etc., provides a potential real-time ecological sight that blind evolution omitted increasing entropy. Modern biophysics, biochemistry, and thermodynamics reinforce these body-environment feedback loops, shifting our trajectory toward conscious, directed co-evolution. Adrian Bejan's Constructal Law unifies biological, inanimate, and technological patterns as flow architectures that optimize current access to minimize irreversibility and reduce entropy. This thermodynamic determinism is mirrored in Nick Lane's bioenergetics, where metabolic networks mitigate entropy decay, and Martin Picard's psychobiology, which links cross-scalar cellular energy dynamics directly to macro-level behavior. Furthermore, Michael Levin's work on bioelectricity highlights how distributed information networks coordinate physical form. Together, these breakthroughs demand that the house be reframed as a low-entropy, life-mimicking dissipative structure. By embedding these systems design-thinking variables into architectural layers—from cells to the biosphere—the built environment achieves thermodynamic decoupling, evolving from a predatory mechanism of ecological degradation into an active, reciprocal node of a wider, interconnected planetary reality. Together, these perspectives challenge the conceptual separation between biological processes and architectural environments. If living organisms are defined by continuous exchanges of energy, matter, and information with their surroundings, then the built environment must also be understood as part of these wider interactions. This takes the Biosphere and the Laws of Physics as a matrix to redefine a new perspective

from the Body to the House, moving toward a more ecological shelter/habitat within the "Web of Life."

2 Why a "House For The Body"

The study 'A HOME FOR THE BODY' is an ongoing research project hypothesizing that architectural design-thinking and construction workflows informed by the human body's anatomical, physiological, metabolical (energy and matter processing), and neuro-cognitive interconnection and information flows, can generate negenentrophyc built environments across nested multi-scalar layers that optimize exergy and minimize localized entropy production compared to conventional designs. The question is, if architectural systems were synthesized through these isomorphic biophysical principles - operationalizing buildings and built environments as open, far-from-equilibrium thermodynamic subsystems structurally coupled with the biosphere, could the house achieve higher standards of thermodynamic efficiency, homeostatic adaptability and autopoietic regenerative capacity, like the self-organizing principles observed in living systems?

3 How to Address the House For The Body

To investigate the proposed hypothesis, this research employs a transdisciplinary comparative analysis between human body biological systems and the architectural design elements of a house (defined as the elementary dwelling unit) taking the following method of analysis:

3.1 Definitions

The Biological Substrate: The Body The human body is a decentralized, self-producing (autopoietic) organism characterized by a 20-year ontogenetic development phase (construction time span) and an 80-year operational lifecycle. Operating across nested biophysical scales—from microscopic eukaryotic cells to macroscopic biosphere networks—the organism maintains metabolic homeostatic stability through eleven synergistic physiological systems. At the cellular foundation, decentralized metabolic networks, such as the mitochondrial Krebs Cycle, process continuous cross-scalar fluxes of energy, mass, and information to generate cellular bioelectricity and fuel systemic functions (thermoregulation, respiration, and waste elimination). Governed by non-equilibrium thermodynamics, the body acts as a highly optimized dissipative structure; it actively minimizes internal entropy production and sustains localized states of high organization (negentropy) by continuously converting environmental exergy into physiological maintenance, somatic repair, and cognitive, collaborative, cooperative, and adaptive performance. The human body's precise phase distribution—dominated by a dynamic liquid matrix (~60–65%) suspended within a minimal, optimized solid tensegrity framework (~30–35%)—is an evolutionary jewel in balancing gravitational resistance with entropy dissipation under the planet physical constraints. Operating across nested biophysical scales, from microscopic eukaryotic cells to macroscopic biosphere networks,

this biological laboratory maintains metabolic homeostatic stability through eleven synergistic physiological systems: the Tegumentary, Skeletal, and Muscular Systems (form the structural, protective, and kinematic matrix); the Nervous, Endocrine, and Immune Systems: Orchestrate real-time information processing and regulatory feedback loops; the Cardiovascular, Lymphatic, Respiratory, Digestive, and Urinary Systems: Act as closed-loop mass, fluid, and resource transport infrastructures. At the cellular foundation, decentralized metabolic networks, such as the mitochondrial Krebs Cycle, process continuous cross-scalar fluxes of energy, mass, and information to generate cellular bioelectricity and fuel systemic functions like respiration, thermoregulation, and waste elimination. Governed by non-equilibrium thermodynamics, the body acts as a highly optimized dissipative structure; it actively minimizes internal entropy production and sustains localized states of high organization (negentropy) by continuously converting environmental exergy into physiological maintenance, somatic repair, and cognitive, collaborative, cooperative, and adaptive performance. This laboratory environment is materially optimized by a precise phase distribution—a dynamic liquid matrix (~60–65%) suspended within a minimal, optimized solid tensegrity framework (~30–35%)—which serves as an evolutionary jewel in balancing gravitational resistance with convective entropy dissipation under terrestrial physical constraints.

THE HOUSE can be understood as an extension of human bodies. Just as cells, tissues, and physiological systems organize the body to maintain life, the house mirrors aspects of bodily physiology and functions as an external regulatory layer that helps stabilize the environmental conditions required for human survival. Through walls, roofs, and envelopes, it acts similarly to bones, muscles, and the integumentary system, providing structure and space while protecting inhabitants from climatic variations, pathogens, and external disturbances, and maintaining controlled exchanges with the surrounding environment. Systems within the house- such as electrical networks, air and water supply, ventilation and thermal control, and liquid and solid waste disposal- operate as infrastructural analogues of physiological systems. In this sense, the house becomes part of the larger logistical network that supports human metabolism and mediates human interactions with the planet. It transforms, distributes, consumes, and stores energy and resources, while facilitating physiological and sociocultural interactions with the environment. By regulating temperature, humidity, light, and air quality, the house reduces the energetic burden placed on the human body to maintain homeostasis, although it externalizes environmental impacts as a consequence of fulfilling human needs. It therefore acts as a technological and spatial prosthesis that extends the body's capacity to resist environmental fluctuations and maintain states of order. Like the body, the house also operates within broader ecological and social systems. Individual dwellings connect to urban infrastructures, communities, and environmental cycles, forming networks that resemble the organization of bodies within the biosphere. Through this perspective, the house can be understood not simply as shelter, but as an adaptive interface between human biological systems and the external world- an architectural extension that supports the continuous flows of energy, matter, and information necessary for human life.

3.2 The Method for a Design Manual

This approach establishes a framework to compare analogous functions across both biological and architectural domains. The proposed methodology is divided into three distinct phases:

Phase 1: Mapping and Measuring
This phase involves an anatomical and physiological mapping quantification and functional categorization of the eleven human body systems equivalent to architectural elements of a house. Acknowledging that the human body operates as a continuous construction site, the study aligns the 80-year life cycle of a building with that of a human body. However, it distinguishes the initial 20 year growth phase (body construction) from the subsequent operational cycle. For the purpose of this comparison, basal metabolic energy associated with physical movement is excluded. Mass and total mass weight is a subject of study.

Phase 2: Biomimetic Translation and Design Parameters
This stage involves the translation of identified biological functions into technical architectural parameters. Biological logics are converted into specific design solutions, where physiological processes- such as metabolic cycles or homeostatic regulation- serve as blueprints for building systems. The goal is to bridge the gap between organic efficiency and tectonic implementation.

Phase 3: Comparative Performance Simulation
A performance simulation will be executed to compare a "biologically-informed" case study against a conventional building model. The analysis focuses on critical indicators such as energy flux, entropy reduction, and resource circularity, evaluating the regenerative capacity and ecological efficiency of the proposed metabolic architectural framework.

Under this proposed framework, architectural design and construction processes that emulate the physiological and metabolic logic of the human body - specifically its regulation of embodied energy and matter flows, and organizational/functional feedback loops, serve as the foundation a low-entropy design manual. A direct analogy is established between the basal metabolic outflows of the human body and the operational and embodied energy management of buildings. Just as basal metabolic processes define the minimum energy required to sustain life-supporting critical functions such as thermoregulation, circulation, and neural activity-buildings necessitate a baseline operational metabolism. This baseline is essential to maintain environmental quality, structural integrity, and technological functionality throughout their 80-year life cycle. By quantifying these parallels, the study evaluates how ´living architectural systems can optimize resource consumption and enhance eco-efficiency.

4 Discussion/Confrontation

4.1 The Metabolic Divergence of Body (Living) and House (Inert)

This research suggests a necessary shift beyond purely metaphorical comparisons between architecture and physiology. By transitioning toward a thermodynamic and entropic analysis of BODY<>HOUSE as a continuous, we reveal critical pathways for a more accurate design approach. Framing the house as an 'inert' structure versus the body as a 'living' one exposes the fundamental tension between Embodied Energy and Metabolic Flux across an 80-year lifecycle.

In this Chapter, the following identified systems that share similar functions in both human physiology and architectural design are studied separately, quantified, and analyzed. It aims to generate conclusions capable of providing further insights for the design manual, as proposed in Phase 2 of the Methodology.

Considering that a HOUSE serves as an external apparatus of the human body, the 'A HOUSE FOR THE BODY' research adopts a model where physiological functions find direct parallels in architectural design and operation. The hypothesis and methodology aim to deepen this principle of engagement. Consequently, the following biological dimensions are particularly relevant, as they follow a logic analogous to building elements, functional operations, and the exchange of energy and mass shared by both the BODY and a HOUSE, allowing a possible comparison:

- **Structural System** (Mass, Structure, Support, and Muscles): The skeletal system provides the rigid framework (load-bearing structure) that protects vital internal components, while the muscular system manages stability, tension (analogous to tensile structures), and kinetic capabilities.
- **Circulatory System** (Flows of Energy, Water, and Air): The cardiovascular system acts as the primary "pumping" and "piping" network responsible for transporting nutrients, gases, and thermal energy. The endocrine system functions as a long-distance chemical signaling network that regulates system-wide processes through the bloodstream.
- **Integumentary System** (Envelope, Int/Ext Interface and Protection): The integumentary system (skin, hair, and gland) operates as a selective barrier - analogous to a building façade -managing thermoregulation, waterproofing, and sensory interaction with the environment.
- **Respiration** (Gas, Water and Thermal exchanges): The respiratory system regulates the intake of O_2 and the expulsion of CO_2, mirroring the ventilation processes and "breathing" capacity of a building's internal volume.
- **Waste Management** (Solid and Liquid Waste flows): The urinary (renal) system functions as a filtration unit that maintains chemical and fluid balance, while digestive system processes raw matter and manages nutrient absorption and waste elimination.
- **Neurological System** (Communication and Cognition, Management, and Energy flows): The nervous system functions as both the "central processing unit" (the brain) and the communication network (the nerves), coordinating physiological processes through real-time responses to stimuli via electrochemical signaling. Brain energy.
- **Regeneration and Autopoiesis** (Protection, Maintenance, and Replication/Growth): The lymphatic and immune systems provide defense and internal "cleaning," which

are essential for maintaining systemic integrity and biological self-maintenance. In addition, cellular and tissue regeneration, together with reproductive processes, provide the biological basis for growth, repair, and generation of new biological units (Table 1).

4.2 Human Body vs Building Systems: A Systemic Mapping

Table 1. Systemic Mapping

Building system	Building components	Body equivalent	Body mass	Body energy
Structure	Concrete, steel, slabs 65–75%, energy 40–60%	Bones + muscles mass	~50–60%	~20–25%
Envelope	Facades, windows 15–20%, energy 20–30%	Skin + fat + hair mass	~15–20%	~5–10%
Distribution+ networks	Pipes, wiring 2–5%, energy 10–15%	Vessels + nerves mass	~5–8%	~10–15%
Thermal + air regul.	hvac, ventilation 1–3%, energy 5–10%	Lungs + thermal reg. mass	~1–2%	~20–30%
Information + organization	Sensors, automation, domotics 0,1–0,3%, energy 1–3%	Brain + nervous mass	~2%	~20%
Energy transform.	Energy generation + storage 1–4%, energy 5–15%	Digestion, cells + mitochondria mass	~2%	~20%
Waste management	Drainage systems 1–2%, energy 1–4%	Kidneys, bladder, intestines mass	~2–3%	~5%

5 Conclusion

In conclusion, this study establishes the BODY<>HOUSE paradigm as a rigorous biophysical and interdisciplinary framework for rethinking architectural design, construction, management, and long-term environmental performance. By neutralizing kinetic locomotion, both the dwelling and the biological body it shelters are analyzed as stationary laboratory environments governed by identical non-equilibrium thermodynamic laws. The comparative metabolic balance reveals that while contemporary buildings rely on fragmented, carbon-intensive, and energy-intensive mechanical systems, the human body operates as a highly optimized, autopoietic dissipative structure characterized by vastly superior exergy efficiency, systemic adaptability, and homeostatic self-regulation through minimal energy expenditure. Through a strict functional analysis of anatomical morphology, physiological feedback, and metabolic networks, this research

isolates comparable mechanisms governing cross-scalar material circulation, fluid thermoregulation, and biochemical waste remediation. This comparative assessment highlights the systemic limitations of conventional architectural and construction models when confronted with contemporary ecological and energetic challenges. Translating the body's highly optimized, low-entropy processes and integrated feedback loops into architectural practice provides a solid scientific and technological foundation for systemic design manuals. By translating biological principles—such as adaptive regulation, circular resource flows, multifunctionality, and resilience—into practical architectural organization, it becomes possible to replace static, carbon-intensive mass with active hydronic networks, closed-loop resource cascading, and sensor-driven envelopes. Consequently, this framework redefines housing not as an industrial product or a passive shield, but as an intelligent, life-mimicking, and environmentally responsive bio-entity, advancing eco-efficient housing models capable of reducing material waste, minimizing localized entropy production, and achieving long-term thermodynamic and biospheric regeneration.

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Urban Solar Carver: A GPU-Accelerated Framework for Solar-Driven Urban Form Finding

Aristotelis Vartholomaios(✉)

University of Thessaly, Volos 383 34, Greece
avartholomaios@uth.gr

Abstract. From early zoning codes to contemporary environmental standards, building volume regulation has served as a primary mechanism for guiding urban form and protecting access to sun and light. The study presents the Urban Solar Carver (USC), a computational framework for generating maximum developable building volumes that protect solar and daylight access. USC builds upon earlier works on solar voxel-based form-finding methods, embedding them into a unified, transparent and reproducible framework. Its main advantage is the integration of GPU-accelerated geometry voxelization, raytracing and solar and sky radiation modelling to evaluate millions of ray–surface–voxel interactions at near real-time speeds. USC is currently under development as a standalone Python library with its own command line interface and connectors to Grasshopper for Rhinoceros 3d. It can generate conventional daylight and time-based solar envelopes but can also perform advanced volume carving using performance-based criteria such as cumulative solar irradiation, passive solar benefit, daylighting benefit, outdoor comfort and even radiative cooling benefit. Some of these features are stable while others are still experimental and require further validation. USC utilizes multiple thresholding techniques, moving beyond fixed-rule envelopes and toward performance-responsive form finding. This level of interaction lets designers and planners experiment with different constraints and immediately see how these choices shape the final massing.

Keywords: solar access · urban planning · urban form · building volume · performance-based design

1 Introduction

Access to sunlight and daylight has long influenced the regulation of urban form [1, 2]. Geometric constraints such as setbacks, height-to-street-width ratios, cut-off planes, and solar access rules are frequently employed to limit overshadowing and maintain adequate environmental conditions for buildings and public space [3]. Interest in solar access has increased in the context of climate-responsive urbanism, where solar exposure affects daylight availability, passive heating, outdoor comfort, and local renewable energy use [4].

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Urban solar-access regulation has gradually evolved from simple geometric rules toward solar-informed volumetric controls. Early approaches relied on setbacks, height-to-street-width ratios, and later sky-exposure planes, as in New York's 1916 zoning framework, to limit building mass [2]. The solar envelope concept introduced in the 1970s marked a shift from fixed angular restrictions to buildable volumes derived from sun-path geometry and protected periods of solar access [5]. Subsequent work expanded this lineage through methods such as solar fans [6], the Residential Solar Block envelope [7], iso-solar surfaces [8], reverse or subtractive solar envelopes [9], and solar-collection envelopes [10]. Digital envelope generation methods have been developed since the 1990s ranging from raster and point-grid approximations [6, 11] to Boolean solid operations [7] and voxel-based approaches [9, 12, 13], each involving trade-offs in precision, robustness, speed, and usability. Some tools implement only a single envelope logic, while others are tied to proprietary software environments or narrow workflows [6]. As solar-access ambitions expand, practical tools for planners and designers remain limited.

This paper introduces the Urban Solar Carver (USC), a computational framework for producing maximum developable urban volumes. USC follows a subtractive logic: a theoretical maximum volume is progressively carved to satisfy environmental constraints. The framework integrates GPU-accelerated voxelization, ray-based volumetric carving, solar and sky radiation modelling, and threshold-based filtering within a single workflow.

2 Tool Description

USC is implemented as a standalone Python library with a command line interface and connectors to Grasshopper for Rhinoceros 3D, enabling both reproducible analysis and interactive design use. A user-defined maximum candidate volume is first discretized into a three-dimensional voxel grid representing potential built mass at any scale (building, block, or neighborhood). The user also defines test surfaces requiring solar or sky access, such as windows, PV arrays, or entire façades. Surface normals must face outward. Rays are traced from sampled points on these surfaces toward multiple directions. Depending on the evaluation mode, these directions correspond to fixed angles, sun positions, or sky patches. Voxels intersected by the rays accumulate either violation counts or weighted obstruction scores. A user-defined threshold is then applied to the resulting voxel score field to determine which voxels are retained.

The workflow consists of three stages: preprocessing, thresholding, and exporting. Preprocessing includes geometry loading, voxelization of the candidate volume, sampling of test surfaces, generation of directional vectors, and per-voxel score computation. Thresholding converts the score field into a binary retention mask using fixed or automatic criteria. Exporting reconstructs the retained voxels into a polygonal mesh with optional cleanup or smoothing (Fig. 1). Parameters are controlled through a YAML configuration file, with optional runtime overrides for batch studies. The framework requires three minimum inputs: a maximum volume mesh, a test-surface mesh, and for climate-based analyses an EPW weather file. The candidate mass is voxelized at a user-defined resolution and test surfaces are sampled into point–normal pairs, controlling the trade-off between geometric fidelity and computational cost.

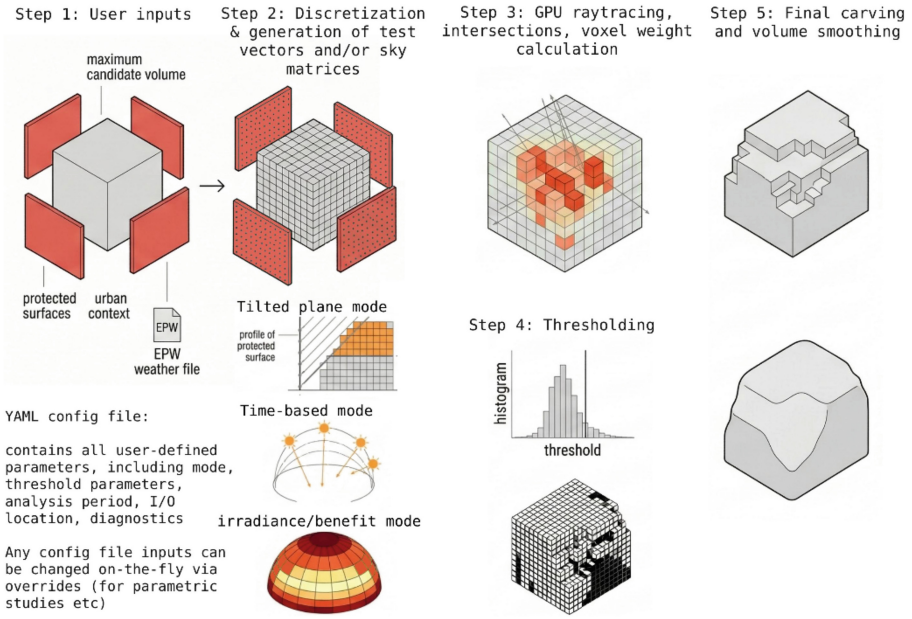


Fig. 1 Overview of USC inputs, modes and execution steps.

Directional data are derived in two ways. For time-explicit analyses, Ladybug generates sun vectors for specified dates and hours. For climate-based analyses, USC uses weighted sky patches derived from annual weather data mapped onto the Tregenza sky subdivision. These create two analysis families: sun-vector methods, which evaluate obstruction at specific times, and sky-patch methods, which evaluate cumulative environmental opportunity over the sky hemisphere. In this study the demonstrated modes are tilted plane, time-based, irradiance, daylight, and benefit.

In *tilted plane* mode, USC applies an angular plane restriction defined by user-specified angles, optionally varying by orientation. Rays cast from sampled surfaces accumulate voxel violation counts according to this directional field. In *time-based* mode, sun vectors for a specified analysis period are generated and rays are cast toward these positions. Intersected voxels accumulate solar-access violations. With a zero-tolerance threshold the resulting mass approximates a conventional solar envelope. In *irradiance mode*, sky directions are weighted by cumulative annual radiation derived from EPW data. Voxels blocking directions with higher radiation receive higher scores and are preferentially removed. In *daylight mode*, sky directions are weighted using a CIE overcast sky luminance distribution. Voxels obstructing brighter sky regions accumulate higher scores. The *benefit mode* weights sky patches according to passive solar usefulness rather than radiation magnitude alone.

Weights are derived from the Ladybug *benefit sky matrix*, generated using Radiance's gendaymtx, which assigns a positive or negative weight to each Tregenza sky patch depending on whether radiation from that direction offsets heating loads or increases cooling loads, given temperature data from the EPW file [14]. The balance temperature

and balance offset parameters control these assumptions and can be refined through building energy simulation.

The computational core of USC evaluates large numbers of ray–voxel intersections. For each sampled surface point, a ray is cast toward each direction in the active set (sky-patch centre or sun position); the total ray count equals the product of test points and directional vectors. USC relies on NVIDIA Warp [15] for sparse voxel representation and ray tracing and on Ladybug Tools [14] for sun-position calculation and climate-based environmental weighting from EPW data. The framework can run on CPU or CUDA-enabled GPUs. Warp provides voxel and raytracing operations while USC handles carving logic, score accumulation, and data flow.

Preprocessing produces either a violation-count field (tilted plane, time-based) or a weighted obstruction field (irradiance, daylight, benefit). During thresholding, weighted fields may be normalized and converted into retention masks using user-defined thresholds or automatic methods such as Otsu or head/tail classification. A retained-fraction strategy can also be used to preserve a specified share of the score distribution. After thresholding, the retained voxel mask is reconstructed into a polygonal mesh with optional smoothing. Intermediate score fields and metadata are stored to enable selective reruns without repeating the full computation.

3 Methodology

USC is applied to a real neighborhood to test its capability to generate and compare alternative solar-driven urban volume controls within the same urban setting. The case study site is in western Thessaloniki, Greece which has Mediterranean climate (40°40′33.4″N, 22°54′47.9″E). This 15 ha neighborhood comprises mainly multifamily apartment buildings.

Building footprints and height data were extracted from OpenStreetMap and used to reconstruct the existing built fabric as a three-dimensional urban geometry (reference case). The same footprints were extruded to a common upper height limit to generate candidate redevelopment masses, retaining the parcel structure while providing a shared geometric basis for comparison. All vertical facade surfaces of the existing buildings were used as test surfaces.

Three USC modes were tested: (i) a fixed-plane scenario using a 45° angular restriction, (ii) a time-based solar-envelope scenario for the winter solstice from 10:00 to 14:00. And (iii) a benefit-based scenario guided by a threshold of 80% useful insolation. Climatic data were provided in EPW format from the IWEC database. For the benefit scenario balance temperature was set to 20 °C with a range of ±2 °C. The value was determined through a simple shoebox simulation of a residential mid-floor apartment using EnergyPlus [16] with construction and occupancy matching the Greek building energy code (KEvAK) specifications. Heating period according to the code for the respective climatic zone (Γ') is from 15th of October to 30th of April. For each scenario, USC carved the candidate masses and generated a final urban volume. These were compared with the existing built form, resulting in four examined cases: existing, fixed plane, time-based, and benefit. All four cases were then subjected to the same ex-post heating period solar simulation.

The comparison used two groups of indicators. Development intensity was described through total built volume, volume per site area, and an estimated mixed Floor Area Ratio (FAR) proxy, assuming an average floor-to-floor height of 3.5 m. Heating period solar performance was described through: (i) total cumulative insolation across all building envelopes and (ii) mean cumulative insolation in kWh/m^2, calculated as the average cumulative energy received per evaluated surface over the examined period. The latter was used as the main solar-performance indicator.

4 Results

Table 1 summarizes volumetric and solar-performance results for the four cases while Fig. 2 visualizes them. The existing neighborhood has a total built volume of 780,400 m^3, corresponding to a volumetric density of 5.08 m^3/m^2 and a mixed FAR of 1.45. Mean cumulative winter insolation is 214.76 kWh/m^2. Calculation time was 47 s per run on a workstation with 64 GB RAM and a GeForce RTX 3060 (12 GB VRAM) for 223 volumes and 1338 test surfaces at a voxel and grid resolution of 0.5 m (over 99 million voxels and 532,581 test points). With 145 Tregenza sky patches the total ray workload exceeded 77 million patch-test point queries per run.

The 45° fixed-plane scenario produced the largest envelope volume (Table 1), representing a 12.1% increase relative to the existing built volume. Mean cumulative insolation increased by +10.9% relative to existing. This scenario also yielded the highest total cumulative insolation due to its larger exposed surface area. The time-based scenario was the most restrictive, reducing total volume approximately 25.7% below the existing built volume (Table 1). Despite this reduction, mean cumulative insolation increased to about 23.5% above the existing condition. The benefit-based scenario nearly matched the volume of the fixed-plane case while achieving the highest mean cumulative winter insolation (Table 1). This represents increases of 34.7% relative to the existing neighborhood, 21.4% relative to the fixed-plane scenario, and 9.0% relative to the time-based case.

The three scenarios reveal clear density–solar trade-offs. The fixed-plane rule retains the largest buildable volume, the time-based envelope secures stronger winter solar

Table 1. Volumetric and winter solar performance comparison of the examined cases

Scenario	Volume (m^3)	Volume/site area (m^3/m^2)	Mixed FAR	Mean cumulative winter insolation (kWh/m^2)	Total cumulative insolation (GWh)
Existing	780,400	5.0	1.4	214	57.15
Fixed plane	874,687	5.7	1.6	238	62.54
Time-based	579,806	3.8	1.0	265	56.01
Benefit	869,904	5.7	1.6	289	60.58

access at the cost of density, and the benefit-based method achieves the highest mean solar performance while maintaining a volume comparable to the fixed-plane case.

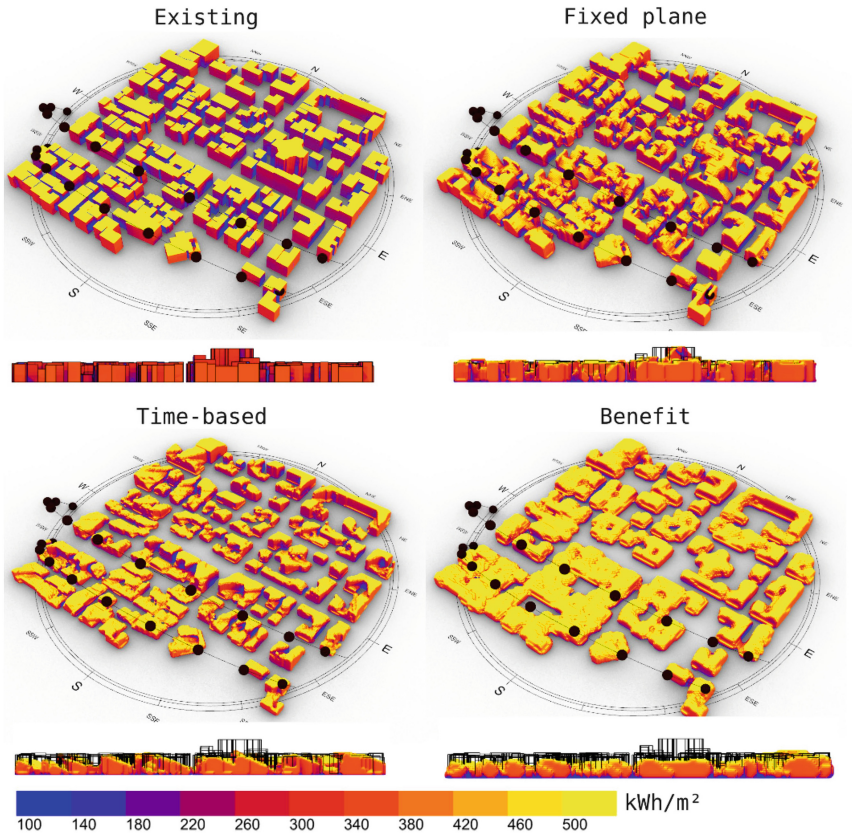


Fig. 2. Average cumulative insolation for the heating period for the four examined cases. Indicative cross-sections illustrate the volumetric differences between the current built form and the three generated envelopes. Sun positions for start and end dates shown as black dots.

5 Conclusions

This paper presented USC, a voxel-based GPU-accelerated framework for solar-driven urban form finding. The framework integrates different volumetric control logics within a common computational pipeline and generates redevelopment envelopes in a reproducible manner. In the neighborhood-scale experiment, three control modes were tested: a 45° fixed-plane rule, a winter-solstice time-based solar envelope, and a benefit-weighted solar criterion. The scenarios produced markedly different density–solar outcomes with the benefit-based scenario retaining nearly the same volume as the fixed-plane case while producing the highest mean cumulative winter insolation among all tested cases.

The analysis is exploratory and limited to a single neighborhood, while the benefit mode relies on simplified assumptions regarding passive-solar usefulness. Despite these limitations, USC can serve as a general computational basis for subtractive urban form finding, allowing different environmental constraints to be compared within the same framework and supporting future research on climate-responsive volumetric controls.

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Beyond the Benchmark: Lessons from Contrasting Intervention Archetypes for Vernacular Buildings in Northern Portugal

Soon Khei[1](✉), Ricardo Mateus[1], Javier Ortega[2], and Raúl Briones-Llorente[3]

[1] ISISE, ARISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal
id10181@alunos.uminho.pt
[2] Consejo Superior de Investigaciones Científicas, ITEFI, Madrid, Spain
[3] Faculty of Sciences, University of Burgos, iENERGÍA, Burgos, Spain

Abstract. The retrofit of vernacular building stock is essential for sustainability, yet standardised solutions often fail to address the typological diversity of mountain regions. Rather than proposing novel designs, this research provides an empirical evaluation of two prevalent, real-world intervention archetypes compared to a baseline scenario corresponding to a building with its original solutions in the Montesinho Natural Park: a non-retrofitted vernacular dwelling (Pathway A), a modern reconstruction using industrial materials (Pathway B), and a sensitive thermal adaptation (Pathway C). Thermal comfort was assessed using the Portuguese adaptive model, contextualised by long-term hygrothermal monitoring and occupancy profiles. Results reveal a critical divergence: the non-retrofitted baseline confirms severe winter discomfort; however, improving this comfort is vital to prevent building abandonment and ensure long-term maintenance. The modern reconstruction (Pathway B)—utilising an internal XPS and plasterboard lining—achieves a rapid thermal response suitable for intermittent use, but represents a "linear substitution". By discarding the original structural solutions, it fails to extend their lifespan and instead generates construction and demolition waste. Conversely, the sensitive rehabilitation (Pathway C) preserves the granite shell (structural circularity), successfully extending the amortisation of the building's existing embodied impacts. However, it risks summer overheating as the non-reversible internal insulation thermally decouples the envelope from the dwelling volume. The findings highlight that sustainable interventions must balance occupant comfort with respect for heritage, prioritising the maintenance of differentiating characteristics and the reversibility of construction works over standardised replacements

Keywords: Adaptive Thermal Comfort · Circular Economy · Hygrothermal Monitoring · Long-Term Monitoring · Low-Carbon Renovation · Vernacular Adaptation

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1 Introduction

The EU's "Renovation Wave" effectively targets urban centres, but its application to rural vernacular heritage creates a complex "sustainability paradox" [1]. Standardised energy efficiency metrics frequently conflict with heritage preservation, compromising cultural integrity [2].

In Portugal's Montesinho Natural Park (MNP), this conflict is acute. Local granite and schist masonry represent inherently circular, "resource-conscious construction" with near-zero embodied carbon [3]. Despite these ecological benefits, the vernacular shell's failure to meet modern winter comfort standards—evidenced by regional monitoring [4–6]—often drives homeowners to replace circular stone shells with linear, industrial materials. The core challenge is negotiating the trade-off between operational comfort, material circularity, and embodied impacts [2].

While previous research characterises MNP's bioclimatic typologies [3, 7], a gap remains regarding occupant interaction. Adaptive behaviours (e.g., adjusting ventilation [8] or clothing [9]) significantly alter energy demand, particularly during intermittent "weekend" occupancy. Addressing this gap, this study correlates long-term hygrothermal monitoring with occupancy profiles across three real-world MNP archetypes. Rather than proposing novel designs, this research provides an empirical evaluation of these actual intervention archetypes, assessing their success in balancing heritage conservation and occupant comfort.

2 Methodology: Defining the Intervention Archetypes

Beyond theoretical abstraction, the study analyses three real-world archetypes located in Pinheiro Novo and Montesinho villages. These cases are not theoretical design proposals, but rather empirical archetypes documenting the divergent physical interventions already executed by homeowners in the region.

2.1 The Case Studies as Strategic Prototypes

The case studies were selected to represent the "Compact Cluster" and "2-Storey" typologies, identified as the most prevalent vernacular forms in the region [3]. Table 1 summarises their characteristics through the lens of circularity and intervention intensity. Crucially, because these are real-world occupied dwellings rather than controlled laboratories, the monitored spaces possess differing geometries and orientations. Consequently, this study does not attempt a direct 1:1 quantitative comparison of identical spaces. Rather, these archetypes are evaluated as representative 'extremes' of the current intervention spectrum—ranging from absolute non-intervention to total structural replacement. They serve as indicative boundaries to expose the real-world trade-offs between thermal standardisation and heritage circularity.

(a) Pathway A (Case 1) Pinheiro Novo. The Non-Intervention Baseline: Representing the "Do Nothing" approach, this dwelling retains its original vernacular configuration: 60–80 cm double-leaf dry granite masonry walls with a hybrid roof (clay and slate). Monitoring focused on a "sandwiched" first-floor bedroom (13.5 m^3) located

beneath the slate roof section. The room has a 0% external Wall-to-Window Ratio (WWR), relying solely on indirect light borrowed from the adjacent kitchen's roof skylights. Consequently, this approach embodies maximum circularity (100% local lithological materials, zero embodied carbon intervention) but relies entirely on the building's original passive capacity to mitigate the climate.

Table 1. Comparative Profile of the three Intervention Pathways

Feature	Pathway A (case 1)	Pathway B (case 2)	Pathway C (case 3)
Intervention logic	Non-Intervention Baseline (Vernacular)	Modern Reconstruction	Adaptation (Sensitive retrofit)
Wall structure	60–80 cm Granite masonry	Reinforced Concrete frame with infilled with thermal clay blocks	Granite masonry (Retained shell)
Insulation	None (Relies on high thermal inertia)	Internal lining system: XPS insulation + Laminated plasterboard	Internal thermal plaster with EPS aggregate
Window ratio (WWR)	0% (Internal/ Indirect light only)	High (> 40% glazed façade)	Low (< 5%)
Circularity profile	Indigenous (100% circular/zero embodied carbon)	Linear substitution (high waste/industrial)	Structural circularity (retains shell/compromised by synthetic plaster)
Heating strategy	Indirect radiant (borrowed heat from adjacent kitchen wood stove)	Mobile convective (electrical unit – on/off demand)	Centralised hydronic (radiators – intermittent use)
Occupancy profile	Continuous (an elderly resident)	Intermittent (2 weeks per month)	Transient (short-term stays)
Thermal goal	Passive survivability	Instant convective comfort (low inertia)	Standardised comfort

(b) Pathway B (Case 2) Montesinho: Modern Reconstruction. Monitoring targeted a rear SE-facing bedroom (38.5 m^3) characterised by high solar exposure (WWR > 40%) and intermittent weekend occupancy. Representing the "Linear" approach, this building is a contemporary reconstruction of a collapsed vernacular ruin. In compliance with strict modern thermal regulations (REH), the original stone load-bearing structure was substituted by a reinforced concrete frame infilled with thermal clay blocks and fitted with double-glazed PVC frames. Crucially, the thermal envelope utilises an

internal lining system of Extruded Polystyrene (XPS) followed by plasterboard. This "box-in-a-box" strategy creates a low-inertia inner surface that thermally decouples the living space from the heavy structure, prioritising rapid convective response over passive stability. While thermally efficient, it represents a "Linear Material Substitution": replacing a monolithic, reusable stone shell with a composite, multi-layered industrial assembly that is difficult to separate or recycle at end of life.

(c) Pathway C (Case 3) Montesinho: Data was collected from a 50.7 m^3 bedroom (SE orientation) located on the upper residential floor. The room features a sloped ceiling that follows the roof pitch, placing the occupant directly beneath the thermal envelope without an attic buffer. Representing the 'Hybrid' approach, this case involves the adaptive reuse of a vernacular two-storey granite dwelling to meet modern habitability standards. The strategy employed a sensitive internal retrofit intervention: the original granite walls were preserved (Structural Circularity), but thermal performance was upgraded using a layer of insulating thermal plaster with EPS beads that is applied internally. This pathway negotiates a trade-off: it saves the embodied carbon of the heavy shell but introduces a synthetic, non-reversible industrial layer to achieve habitability. Crucially, the direct exposure to the roof (lacking a buffer zone) exacerbates summer overheating, as the internal insulation traps solar gain entering through the unbuffered slate roof envelope, creating a ´thermos effect´ during summer.

2.2 Assessment Metric: The Adaptation Gap

The study evaluates thermal resilience using the Portuguese Adaptive Comfort Model [10], specifically calibrated for the local climate. Unlike static ISO 7730 standards, this model defines comfort boundaries based on the 7-day running mean outdoor temperature (Θ_{rm}), acknowledging the occupant's ability to adapt in naturally ventilated spaces.

Consistent with ISO 7726 [11], indoor air temperature (Θ_{int}) serves as a robust proxy for operative temperature (Θ_{op}). In Case 1, high inertia and indirect heating minimise radiant asymmetry. In Case 2, the use of a mobile electrical heater provides direct convective heating which, combined with the low inertia plasterboard lining and internal insulation, ensures rapid air-surface equilibrium. Similarly, Case 3's internal insulating thermal plaster decouples the surface temperature from the structural mass, preventing radiant cooling during intermittent occupancy.

The comfort limits for Category II (Normal Expectation) are calculated using the algorithm calibrated by Matias 2010 [10]:

$$\Theta_c = 0.43 \cdot \Theta_{rm} + 15.6 \left(\pm 3.0^{\circ}\mathrm{C}\right) \tag{1}$$

where Θ_c is the operative comfort temperature. For the heated/intermittent cases (Cases 2 and 3), the ASHRAE 55-based adaptive coefficient [12] (cited by [10]) is applied to account for higher user expectations:

$$\Theta_c = 0.31 \cdot \Theta_{rm} + 17.8 \left(\pm 3.5^{\circ}\mathrm{C}\right) \tag{2}$$

Performance is reported as Comfort Compliance (%), defined as the percentage of hours in which the indoor operative temperature falls within the calculated bandwidths.

2.3 Monitoring Protocol

Hygrothermal monitoring utilised Testo 174H dataloggers (accuracy: ±0.5 °C/±3% RH). Data was recorded at 30-min intervals over a continuous annual cycle (Feb 2024–Feb 2025) to capture seasonal inertia lags.

To prevent occupant interference and to comply with owners´ requirements, sensor heights are varied: Case 1 was monitored at the sleeping plane (0.7 m), while Cases 2 and 3 were monitored at elevated positions (2.0–2.5 m). While thermal stratification implies these elevated sensors record temperatures slightly higher than the occupied zone, this methodology ensures a conservative assessment of winter discomfort (actual conditions are colder) and captures worst-case heat accumulation risks during summer.

3 Results: The Comfort Cost of Intervention

3.1 Winter: The Survivability Deficit

During the heating season, all three pathways struggle to meet Category II comfort standards (18 °C–25 °C) without active energy (Table 2), but their failure modes differ significantly:

(a) Pathway A (Non-Intervention): Records 0% comfort compliance, with indoor temperatures anchoring to the ground temperature (~8–11 °C). While the massive granite walls dampen daily fluctuations, the lack of insulation results in a steady-state thermal crypt. For the continuous elderly occupant, survival depends entirely on personal adaptation (heavy wool clothing) and a localised radiant heat source (wood stove), confirming that the vernacular shell fails modern static comfort metrics.
(b) Pathway B (Heavy Reconstruction): Despite deep renovation (concrete/XPS), the unheated baseline is only marginally better (13.9% compliance). However, the *responsivity* is the key differentiator. The low-inertia internal lining allows the intermittent occupant to heat the space rapidly using the mobile electrical heater. This rapid thermal response suits the intermittent occupancy profile but renders the building rapidly uncomfortable during power outages, lacking the passive survivability of the high-mass vernacular.
(c) Pathway C (Sensitive Rehabilitation): The sensitive retrofit performs poorly in winter (7.8% compliance). The internal EPS thermal plaster isolates the room from the granite mass. Without a continuous heat source to "charge" the stone, the room cools rapidly, behaving more like a lightweight tent than a massive cave.

3.2 Summer: The Maladaptation Risk

Summer highlights critical pathway trade-offs (Table 2):

(a) The Thermos Effect (Pathway C): Case 3 exhibits the lowest summer compliance (53.0%), frequently overheating above 27 °C. The internal EPS thermal plaster layer traps solar gain inside, preventing the massive granite wall from acting as a heat sink. Consequently, occupants face a stifling environment that cannot passively cool down at night. While this thermally decoupled, low-inertia space would respond rapidly if active air-conditioning were installed, its inability to manage heat passively represents a fundamental bioclimatic failure for a vernacular structure.

(b) The Ventilation Paradox (Pathway B): Surprisingly, the concrete box achieves the highest summer comfort (94.3%). This is not due to materials, but operability. The high Window-to-Wall Ratio (WWR) allows the weekend user to induce rapid cross-ventilation, dumping heat instantly.
(c) The Inertial Drag (Pathway A): The vernacular baseline achieves moderate success (59.5%) but suffers from "Cold Lag" in spring and "Heat Retention" in late summer, as the massive walls are slow to adjust to seasonal shifts

Table 2. Annual Portuguese Adaptive Comfort Compliance (Category II EN 16798–1) [10, 13]. Table format and methodology adapted from [14].

Season	Case 1 (Baseline)	Case 2 (Reconstruction)	Case 3 (Rehabilitation)
Winter	0.0%	13.9%	7.8%
Spring	0.0%	21.9%	73.0%
Summer	59.5%	94.3%	53.0%
Autumn	0.1%	14.3%	35.2%

4 Discussion: Negotiating Circularity and Comfort

The results highlight a fundamental conflict: the intervention that delivers the best *instant* comfort (Pathway B) is the most destructive to circularity, while the most circular option (Pathway A) is thermally obsolete.

4.1 Structural vs. Material Circularity

In order to evaluate the circularity implications of each intervention, defined here as the strategy's success in extending the lifespan of existing materials and avoiding the introduction of non-reversible industrial waste, this study defines a two-tier assessment:

(a) Pathway B (Case 2) represents a Linear Substitution. While this intervention successfully achieves the highest summer comfort compliance (94.3%) and provides rapid operational responsivity for intermittent winter use (as detailed in Sect. 3), this operational success comes at the severe cost of structural circularity. Rather than sourcing local granite to complete the structural shell, the deficit was bridged using non-reversible industrial materials (reinforced concrete, thermal clay blocks, and XPS). By discarding the durable vernacular shell, this pathway represents a missed opportunity for lifespan extension and generates unnecessary construction and demolition waste, prioritising short-term thermal standardisation over long-term material reuse.
(b) Pathway C (Case 3) represents Structural Circularity. By retaining the granite shell, it successfully extends the amortisation of the building's existing materials [2]. However, as evidenced by the severe summer overheating (53.0% compliance) detailed

in Sect. 3, the application of a non-reversible EPS-based thermal plaster creates a maladaptive thermal environment. The internal insulation thermally decouples the envelope from the dwelling volume, trapping solar gain and negating the passive heat-sink potential of the granite. Furthermore, unlike traditional earth mortars, the synthetic plaster contaminates the stone rubble, compromising future material circularity. True circularity in this context requires substituting non-reversible synthetic layers with bio-based, reversible alternatives (e.g. cork or hemp) that respect the building's passive physics.

4.2 Occupancy-Aligned Interventions

The failure of Pathway C and Pathway A suggests that one standard intervention cannot serve all users. We propose an Occupancy-Based Framework:

(a) For Intermittent Use (e.g. holiday houses): High-mass interventions are inefficient because they take too long to heat. A box-in-a-box lightweight strategy (similar to Pathway B but reversible) is more energy-efficient for 2-day stays.
(b) For Continuous Use (e.g. permanent dwellings): The Non-Intervention approach (Pathway A) is insufficient. However, deep encapsulation (Pathway C) risks overheating. The optimal circular strategy is Selective Insulation: insulating only the roof (major heat loss) and the north façade, while leaving the south granite internally exposed to take advantage from the thermal inertia and act as a heat sink, preserving the lithological inertia that stabilises the home.

5 Conclusion

This study compared three intervention archetypes in the Montesinho Natural Park (MNP) to evaluate the trade-off between material circularity, comfort, and heritage. The results confirm that heavy reconstruction (Pathway B) achieves a rapid thermal response suitable for intermittent use but constitutes a circularity failure; by discarding the durable vernacular shell, it fails to extend the lifespan of original materials and generates unnecessary construction and demolition waste. Conversely, sensitive retrofits (Pathway C) preserve the granite structure, successfully extending the amortisation of the building's existing embodied impacts, but risk maladaptation (summer overheating) if non-reversible synthetic insulation interferes with the building's passive physics.

Ultimately, sustainable renovation in MNP cannot be a binary choice between preservation and modernisation. It requires a negotiated intervention strategy that aligns the intervention intensity with the Occupancy Profile. Furthermore, the extreme archetypes evaluated here highlight that the optimal solution does not lie at the boundaries of total preservation or total replacement, but rather in intermediate, hybrid approaches. These findings have critical implications for the circularity of the wider built environment: they demonstrate that sustainable interventions must balance occupant comfort with respect for heritage, prioritising the maintenance of differentiating characteristics and the reversibility of construction works over standardised replacements. For the region's dominant stone masonry typology, the most circular future lies not in replacing the granite, but in surgically enhancing it—using bio-based materials to fix the winter gap without destroying the summer resilience that this geology has provided for centuries.

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Monitoring the Advance of Light Pollution Through Remote Sensing Data: Case Study in a Brazilian City

Ricardo Nacari Maioli(✉), Ludmila Brunow Orlandi, Izabela Uliana Pellegrini, Victor Moura Bussolotti, and Cristina Engel de Alvarez

Programa de Pós-Graduação em Arquitetura e Urbanismo, Universidade Federal do Espírito Santo, Vitória, Brazil
ricardo.maioli@ufes.br

Abstract. Light pollution is a growing global issue that interferes in the life cycle of humans, fauna, and flora, so it's necessary to identify and understand its causes to propose mitigation strategies. This research aims to analyze the evolution of the radiance using remote sensing data in Serra, a Brazilian city of approximately 520,000 inhabitants, the most populous municipality in the state of Espírito Santo, in the southeastern Brazil. Serra had one of the highest growth rates in the state, requiring light pollution monitoring due to its potential impact. The research was based on annual remote sensing images acquired from the Visible Infra-red Imaging Radiometer Suite (VIIRS). Light pollution in the area analyzed was monitored using maps with radiance emission records generated from 2012 to 2024. These data were cross-referenced with population urban indicators. The methodology used made it possible to identify areas of the city with higher levels of light pollution, which can assist government officials and urban planners in creating control policies or other mitigation actions. The results show a significant increase in light pollution during the period analyzed, higher than expected due to population growth. The lighting of public squares and main avenues is responsible for high levels of radiation, and the urbanized area of the city, which concentrates 99% of the population, is subject to high levels of light pollution, affecting the health of its inhabitants.

Keywords: Artificial Light at Night · Night-time Light · Radiance · VIIRS · Artificial Lit Surface

1 Introduction

Light pollution is a growing problem on Earth and comes with negative consequences for fauna, flora, and human-being [1–3]. This problem has been known for several decades [4], but new discoveries are being made regarding the loss of darkness or the impact of Artificial Light at Night (ALAN) on living beings [3, 5]. Studies indicate that ALAN can cause a decrease in melatonin production at virtually any exposure intensity and, consequently, disrupt the human circadian cycle, for example [6]. The increasing use of artificial light at night is potentialized by the new lighting technologies with higher efficacy and lower cost of light, creating a rebound effect [1, 7].

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Remote sensing of night lights is an important tool to observe human activities from space and, more recently, to monitor the light pollution of a region [8, 9]. Despite limitations such as low resolution and the impact of weather conditions, the use of satellite images of night-time lights can provide important information for urban management and planning [10]. This kind of investigation is used in other studies around the world [10–12].

Monitoring nighttime lights in growing cities can provide important information for urban management and planning. This study analyzes light pollution in the city of Serra, state of Espírito Santo, on the coast of Brazil (Fig. 1), which has experienced continuous population growth in recent years.

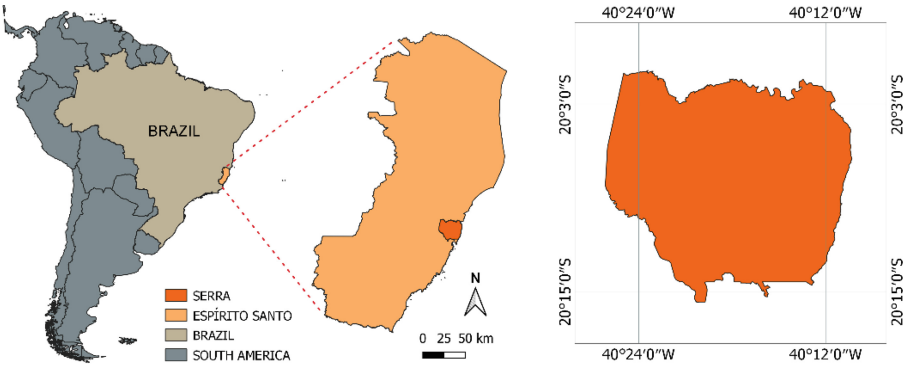


Fig. 1. Location of the municipality in relation to the state and the country.

The main objective of this study is to analyze the light pollution from 2012 to 2024 in Serra (Brazil) using remote sensing data to identify the main sources, changes and trends. This investigation uses maps to highlight the levels of radiance present in the analyzed area over this period and compares them with the type of land occupation. Thus, it is expected that it can be helpful in urban management.

2 Method

2.1 Research Area

Serra has an area of 547,631 km^2 and a population of 520,653 inhabitants. It is the most populous municipality in the state of Espírito Santo and has a population density of 950.74 inhabitants per km^2. It has the sixth highest Gross Domestic Product (GDP) *per capita* in the state and ranks among the top 10% in the country. Its urbanized area corresponds to just over 17% of the territory [13], but the municipality's urbanization rate is over 99.5% and less than 0.5% of the population is rural.

The municipality has industrial areas distributed in specific points of its territory, which concentrate a large part of the region's industries. This is due to the creation of industrial centers, a process that began in the 1970s to meet the growing demand of

the metropolitan region, culminating in the largest industrial hub in the state. Consequently, in the following decades, the municipality experienced robust demographic and economic growth [14] and now accounts for 13.6% of the state's population [13]. It should be noted that industrial, demographic, and economic growth can be indicative of increased light pollution [15], which makes Serra an interesting case study.

2.2 Extraction and Organization of Radiance Data

Light pollution data were extracted from a portal that provides annual maps of nighttime lights (www.lightpollutionmap.info), used by other studies [5, 10, 16]. At the time of writing, global maps containing radiance emissions ($nWcm^{-2}\ sr^{-1}$) were available for the years 2012 to 2024. These maps, in GeoTIFF format, were inserted into QGIS software for georeferenced spatial representation and contained radiance data for each pixel in the image. The software was used for visualization, creation, and editing of maps, as well as data analysis (https://qgis.org/). The radiance data contained in the pixels were divided into value ranges, with each range represented by a specific color in a predefined gradient, facilitating the analysis and comparison of the data obtained. A spreadsheet with radiance data was also generated from the maps produced in the software. The data for each year was then compiled and organized for analysis of the evolution of light pollution over the period evaluated.

2.3 Selection of Methodology

Light pollution was analyzed using statistical indicators such as the sum of radiance values (Rad. Sum), radiance per unit area (Rad. Mean), and radiance per 1000 inhabitants (Rad./1 k Pop.) [5], to compare the data obtained with other studies and to analyze its evolution over time.

Another way of evaluating light pollution, proposed by Górniak-Zimroz *et al*. [10], is to organize its levels into five classes, from No pollution to Very High pollution. In the present study, an adaptation of the last class was proposed, since the values found may exceed the originally proposed limit, resulting in the following scale: 0–1.5–3.0–15.0–higher ($nWcm^{-2}\ sr^{-1}$). This methodology can help identify social and environmental elements that emit light or are subject to it [10]. Here, this methodology was used to analyze the spatial coverage of each class and the land use and occupation subject to it. However, this method restricts the possibilities for analyzing radiance data, so a complementary analysis was proposed in the sequence.

Therefore, another method used in the research was the spatialization of radiance levels divided into more bands, including higher values, proposed to facilitate the identification of areas that record radiance peaks in the city. A similar method was used in the research by Maioli *et al.* [16] for the analysis of annual maps, however, with another scale of radiance levels. Thus, this study proposed a scale of radiance levels divided into 10 bands, each band being limited to twice the value of previous one (0–0.5–1.0–2.0–4.0–8.0–16.0–32.0–64.0–128.0 $nWcm^{-2}\ sr^{-1}$). With the production of maps using this new classification, areas with higher radiance levels became visually prominent. Next, the type of land use present in these brighter regions was verified, an important analysis to assist public authorities in taking mitigating measures.

3 Results and Analysis

The number of inhabitants of Serra growth 27,2% in 12 years (2010–2022) [13], observed in Fig. 2a, but the sum of total radiance observed in this city increased 65,4% (2012–2024). This means that the amount of radiance emitted per inhabitant is growing rapidly, reflected in an increase in *per capita* emissions in the range of 30%. Contrary to what is observed in most developed countries, developing countries show a growing trend in nighttime light pollution mean and *per capita* [11]. The *per capita* radiance of the municipality reached 99.5 nWcm^{-2} sr^{-1} for every 1,000 inhabitants, which is higher than the national mean of 45.2 nWcm^{-2} sr^{-1} [17].

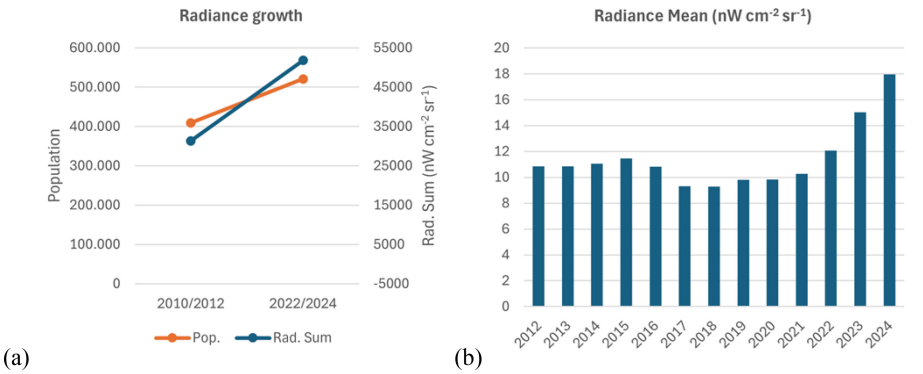


Fig. 2. Population growth and total radiance emissions over a 12-year period (a). Evolution of mean radiance between 2012 and 2024 (b).

In the middle of the period analyzed, it was possible to identify a decrease in radiance levels, which may be caused by different reasons [9, 11, 12]. However, an alarming increase in emissions was observed in sequence. The last three years have presented a continuous elevation of radiance levels (Fig. 2b). This fact matches with the gradual replacement of the street lighting system. The transition of streetlamps technology to LED in the city started in 2020 and was completed in 2024, and the amount points of light grows caused by the expansion of urban areas and the number of luminaires. The municipality reported that the new lights installed were 5000 K in color temperature. It should be noted that the sensitivity limitation of VIIRS DNB for wavelengths below 500 nm may suggest a false reduction in light pollution in cities that have transitioned to LED lighting [18].

In contrast to what was observed in the neighboring municipality, the state capital, which reached an average of 32.74 nWcm^{-2} sr^{-1} in the period [16], the mean radiance levels Serra between 2012 and 2024 was 11.43 nWcm^{-2} sr^{-1}, exceeding the national mean by 47 times. It is worth noting that the city's average radiance is on the rise and reached an average of 17.97 nWcm^{-2} sr^{-1} in the last year analyzed, close to the level recorded in Hong Kong [12], while the average for Brazil is 0.24nWcm^{-2} sr^{-1}.

In this study, the light pollution classification method based on Górniak-Zimroz *et al.* [10] was used, divided into five classes, to analyze the coverage of each class in

the territory. As a result, the areas corresponding to Very High Pollution increased by 21.3% in comparison between 2012 (Fig. 3a) and 2024 (Fig. 3b), reaching a portion corresponding to 29% of the territory. Another class that increased significantly in the period was the area covered by Medium Pollution, registering a growth of 41,8%.

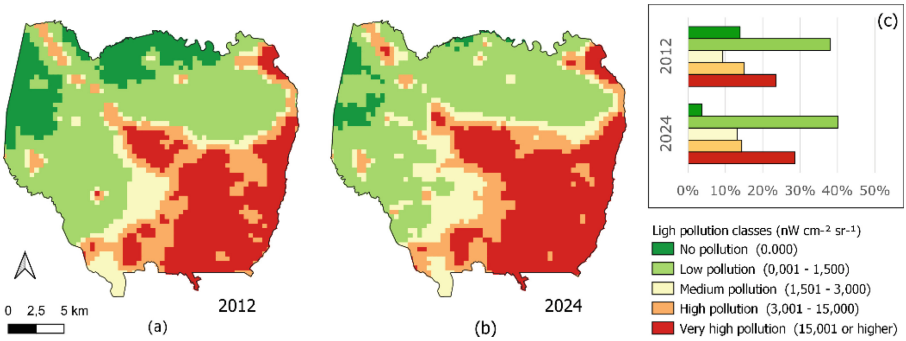


Fig. 3. Maps of the study area drawn up from light pollution classes, based on Górniak-Zimroz *et al.* [10] for the years 2012 (a) and 2024 (b), with a comparative graph between them (c).

One of the aggravating factors of light pollution in the region, observed in the study, is a 72.6% decline in areas identified as No Pollution, which was limited to only 4% of the territory in the last year analyzed (Fig. 3b). This indicates an increase in light pollution in non-urbanized areas of the city, which can have negative impacts on the ecosystems of these regions. The other classes of light pollution registered a variation of approximately 5% in the total quantity, that is, less significant, but with a partial shift in the areas covered by them (Fig. 3c).

Next, the social and environmental elements in each class were identified by analyzing land use and occupation. It was observed, therefore, that the area covered by the Very High Pollution class on the 2024 map corresponds to the urbanized area. Thus, it is estimated that approximately 99% of the municipality's population lives in a region classified as Very High Pollution (Fig. 4b). Some buildings were found outside this zone, but subject to some level of light pollution.

Considering only its urbanized land, it was possible to highlight in the analysis the presence of urban environmental protection zones [19] close to the city's residential and industrial areas located in regions with Very High Pollution in 2024 (Fig. 4a). This fact can have a negative impact on local fauna and flora, as they are influenced by ALAN from urban lighting [1], which remains on throughout the night.

Nevertheless, this approach to radiant classification has some limitations, such as the absence of highlighting of the brightest pixels in the study area. To address this, a 10-class scale was used to facilitate identification. This made it possible to identify the pixels in the municipality with the highest radiance levels and the type of land use and occupation present in the region with the most intense brightness (Fig. 5).

Despite the large presence of industries in the municipality, some of them operating 24 h a day, among the areas responsible for the highest emissions, some had little or no industrial activity. The areas that stood out with the highest radiance indices are

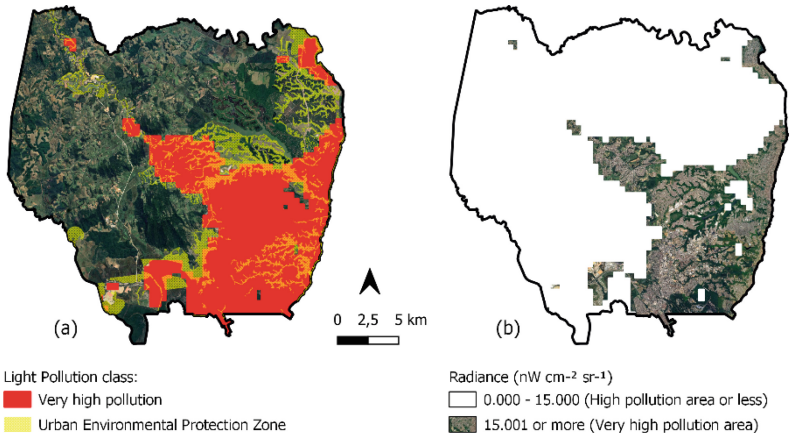


Fig. 4. Maps of Serra with satellite images recorded using QGIS software. (a) Very High Pollution area (in red) covering Environmental Protection Zones [19] (in soft yellow). (b) Urbanized portion of the territory corresponding to the Very High Pollution class.

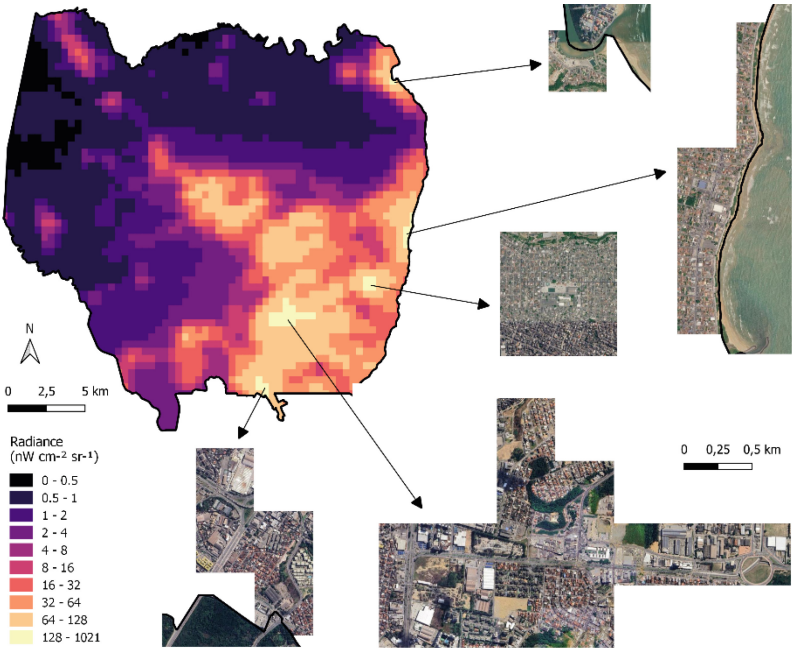


Fig. 5. 2024 light pollution map highlighting the areas with the highest radiance levels.

beachfront regions, public squares, and major avenues, characterized by the presence of commercial establishments and few industries. Among the highlighted sections, two public squares appear to be responsible for excessive light emissions into space. It should be emphasized that, in 2024, the municipality expanded the lighting system on some of

the main avenues, which may have contributed to an increase in emissions that year in certain sections of the city.

Similar results were found in research conducted in China, where residential and commercial areas achieved higher mean radiance values, with 48 $nWcm^{-2}$ sr^{-1} and 54 $nWcm^{-2}$ sr^{-1}, respectively, than industrial regions, which recorded 38 $nWcm^{-2}$ sr^{-1} [12].

4 Conclusions

The research aimed to analyze the evolution of light pollution in the city of Serra (Brazil) from 2012 to 2024 based on satellite data, a process carried out through the classification and subsequent identification of areas with recorded levels of radiance. The method used proved to be effective in identifying the spread of light pollution and the brightest areas of the city. 99% of the municipality's population is subject to high levels of light pollution, which can be harmful to the health of its residents, while environmental preservation areas located near urbanized regions are also impacted by this level of pollution, probably affecting the ecosystems present there. The municipality recorded an increase in *per capita* light emitted into space, as well as an increase in total light emitted over the last three years of the analysis, and the problem may be even more serious due to limitations of the nighttime light sensor.

A survey closer than satellite data, such as local measurements or drone analysis, can provide more accurate data on the main sources of local light pollution. However, conducting the first approximation through the evaluation of satellite data has proven to be an interesting strategy for assessing the evolution of light pollution and that can be reproduced in similar situations.

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A Regenerative Framework for the Renovation of Existing Buildings

Cristina Jiménez-Pulido(✉), Ana Jiménez-Rivero, and Justo García-Navarro

Universidad Politécnica de Madrid, 28040 Madrid, Spain
cristinajpulido@gmail.com

Abstract. Regenerative development offers a promising pathway to address the transformation required in the building stock to meet climate commitments. However, its application to existing buildings remains largely unexplored. Supporting this transition requires instruments aligned with regenerative ambitions. This study proposes a regenerative framework for existing buildings to support decision-making from the evaluation phase onward. The framework adopts a hierarchical structure based on three pillars—Place-based (Pb), System-based (Sb) and Positive-oriented (Po)—that represent the core ambitions. These pillars are articulated through nine attributes: Building pre-conditions, Site usage patterns, and Location sensitivity (Pb-1,2,3); Long-term vision, Closed-looped systems, and Lasting value (Sb-1,2,3); Empathy with occupants, Responsible and nature-based elements, and Creativity and Innovation (Po-1,2,3). Together, these elements provide a structured basis for advancing the regenerative transformation of existing buildings. By organising regenerative ambitions into a hierarchical and assessment-oriented structure, the framework provides a coherent basis for supporting the integration of regenerative principles into evaluation processes for building maintenance and renovation. In a prospective manner, the study explores the integration potential of the framework with current evaluation instruments—institutional initiatives, Sustainability Certification Systems and pioneering assessment tools—highlighting their potential role in supporting regenerative approaches to building renovation.

Keywords: Regenerative framework · Evaluation instruments · Sustainability certification systems · Existing building renovation · Regenerative approach

1 Introduction

Cities and buildings are key to reducing environmental impacts and to mitigating climate change. The renovation of the building stock represents both a challenge and an opportunity for long-term sustainable development. Regenerative development is increasingly considered necessary to redefine sustainability (e.g., [1, 2]). It challenges traditional building-centric approaches to maintenance and renovation [2], and moves beyond a conservative impact-reduction vision towards buildings capable of generating economic, social, environmental, and intangible benefits. Therefore, the regenerative approach is particularly well-suited to the transformation required in the building stock.

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This shift in perspective also calls for updated instruments to make decisive progress. Although regenerative principles are increasingly explored in relation to buildings and urban environments, studies developing these principles, and proposing operative processes remain scarce [3], especially for existing buildings. Early attempts to incorporate regenerative principles into instruments have been noted [4], but overall advancement remains moderate. Instruments grounded in regenerative principles could support both planning and implementation of regenerative actions, with assessment tools being particularly relevant for practical application. To obtain regenerative outcomes, assessment procedures for existing buildings must align with the goals envisioned by the regenerative paradigm. However, current tools—with Sustainability Certification Systems (SCSs) playing a leading role—rarely focus on either existing buildings or regenerative sustainability [5].

To address this gap and promote regenerative decision-making, this study aims to lay the foundations for integrating the regenerative perspective in practice-oriented instruments for existing buildings. Specifically, our objective is to identify the regenerative elements subject to be integrated into assessment processes for existing buildings and to outline a framework to support future implementation. The contribution of this work lies in reorganising existing concepts and formalising regenerative ambitions into a hierarchical and assessment-oriented structure tailored to building stock transformation.

The following section provides the methodological approach adopted, analyses the regenerative sustainability paradigm in relation to existing buildings and presents the proposed framework. Section 3 examines links between the regenerative framework and current evaluation instruments to explore pathways for application. The final section presents the conclusions of the study.

2 Conceptual Development of the Regenerative Framework

2.1 Methodological Approach

Structuring the shift towards regenerative sustainability into an operational framework is challenging [6], specifically for buildings in use given their multidimensional nature. A literature-informed conceptual analysis was conducted to examine both the regenerative sustainability theory and evaluation instruments, with a focus on their applicability to existing buildings, their structures and sustainability approaches. Regarding the study of regenerative theory to identify regenerative ambitions applicable to existing buildings, a literature specifically addressing this paradigm was first reviewed. The review was expanded to include related literature areas, namely circularity, resilience, and traditional sustainability, based on conceptual linkages identified.

Regarding evaluation instruments, literature was collected with a focus on pioneering regenerative-oriented tools and emerging instruments aligned with regenerative thinking. Additionally, literature on Sustainability Certification Systems (SCSs), complemented by previous review work [5], and institutional assessment initiatives were analysed. Evaluation instruments can help bridge theory and professional practice, and SCSs, because of their widespread use, can provide useful insights and may support the integration of regenerative approaches into practice. Furthermore, given the relevance of regenerative

approaches to global and European challenges, examining their links with institutional instruments was also considered essential.

For regenerative sustainability to succeed in existing buildings, it is essential to understand the implications of adopting a regenerative approach and to translate regenerative principles into assessment-oriented elements. Rather than proposing new regenerative concepts, the study reorganises existing ones into an assessment-oriented framework tailored to existing buildings, capable of systematically structuring the particular regenerative ambitions. Based on the review conducted, key regenerative features and recurring themes were identified and, through an iterative process, synthesised into the main regenerative ambitions for existing buildings (see Fig. 1). These elements were grouped around conceptual pillars, organised into attributes for building evaluation purposes. This process enabled the development of a hierarchical regenerative framework intended to support regenerative evaluation and renovation for existing buildings.

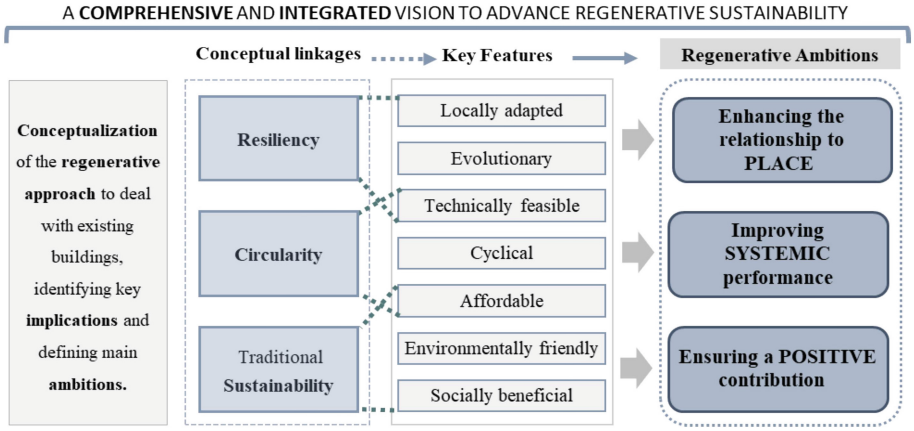


Fig. 1. Conceptual analysis conducted to examine the regenerative sustainability paradigm.

2.2 Identifying the Regenerative Ambitions to Be Pursued for Building Stock

The regenerative sustainability linked to the built environment emphasises two key concepts, as Orova & Reith [1] highlighted: (a) the co-evolution between people and nature; (b) a proactive vision aimed at reversing environmental degradation by generating benefits. Instead of "doing less harm" as in traditional sustainable buildings [6], regenerative buildings aim to produce net-positive impacts. In practice, this involves adapting decisions to the particular circumstances of each building, restoring technical, social, and natural systems as a first step towards generating positive outcomes (that is, regeneration).

The change of vision implied by the regenerative paradigm foregrounds place as a generator of social and natural capital [4, 7]. To transform existing buildings into regenerative ones, a systems-based approach is paramount, as the building stock forms a complex socio-technical-natural structure with multiple interconnected dimensions and stakeholders. This highlights the need to reconsider the notion of place in existing

buildings. The history and potential of the living environment must be acknowledged, together with the functioning dynamics among existing buildings, to understand context, preconditions, and priority needs.

Closing loops during building operation is essential. Lifecycle thinking must therefore be applied to guide decisions, considering the building's lifespan [8] as well as the functionality and maintainability of its components. Long-term resource efficiency, to save energy and material sources, requires extending building use while improving performance, highlighting the relevance of regenerative approaches to buildings maintenance. Successful regenerative interventions must involve strengthening vital relationships [3], in partnership with nature. This requires a long-term vision to account for overall impacts and complex interactions with context. Tailored regenerative roadmaps for each building could reduce negative impacts and generate positive contributions at multiple scales, enhancing cultural identity and supporting environmental health and biodiversity.

2.3 Proposed Regenerative Framework for Existing Buildings

Pursuing regenerative results when dealing with existing buildings requires considering all regenerative ambitions as pillars underpinning decisions, and adopting a broader, holistic, and integrated approach. Three Regenerative pillars—Place-based (Pb), System-based (Sb), and Positive-oriented (Po)—form the backbone of the proposed framework, providing its first hierarchical level. These pillars directly relate to the categories proposed by Kamari et al. [9] for renovation processes ("Functionality", "Feasibility", and "Accountability"). A second hierarchical level is defined through three attributes for each pillar, which intends to support the framework applicability and decision-making. These elements together, pillars and attributes, shape the regenerative framework (see Fig. 2), intended to provide guidance for action in existing buildings.

The **Place-based pillar** is shaped by: Building pre-conditions (Pb-1); Site usage patterns (Pb-2), focused on physical dynamics and geographical characteristics; Location sensitivity (Pb-3), related to intangible values of the place. Regenerative decisions should be adapted to the building's existing physical pre-conditions, usage patterns, and local context, seeking harmony with place and co-evolution [2]. However, buildings and urban areas are often treated separately [10]. Given that existing buildings are at some point in their lifespan, a comprehensive assessment of their physical and functional condition is paramount to ensure feasibility and anticipate impacts of solutions.

The **System-based pillar** comprises: Long-term vision (Sb-1); Closed-looped systems (Sb-2); Lasting value (Sb-3). A systemic approach is fundamental because existing buildings are embedded in complex and evolutionary socio-technical-natural systems [7]. Regenerative interventions must not only consider multiple scales, scenarios and long-term implications, but also identify circular flows. Closing loops depend on stakeholder engagement, particularly those involved in resource and service provision. A holistic view permits identifying interrelationships among the different facets—where human factors are key—and enables the evaluation of multiple impacts of decisions. Economic considerations are also essential to ensure feasibility of measures and to spread the benefits. Ultimately, regenerative solutions should produce lasting improvements.

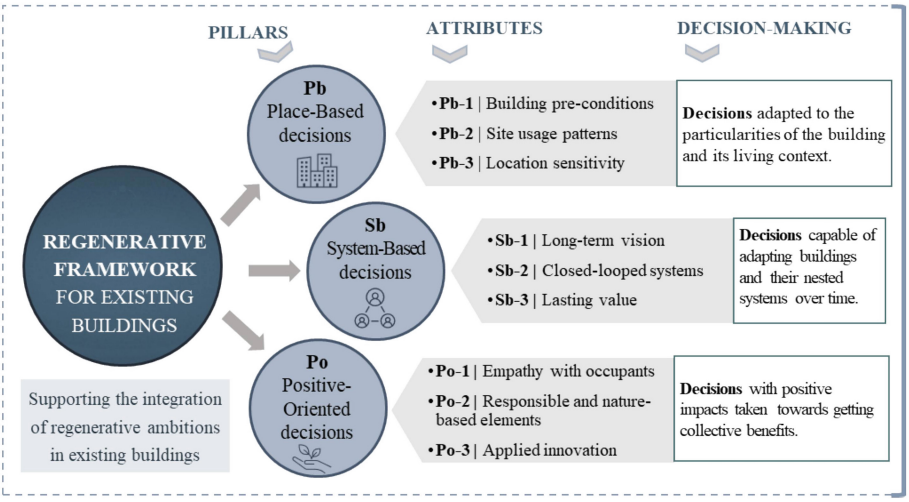


Fig. 2. Proposed Regenerative framework for dealing with existing buildings.

The **Positive-oriented pillar** comprises: Empathy with occupants (Po-1); Responsible and nature-based elements (Po-2); Creativity and Innovation (Po-3). Positive-oriented measures enhance human wellbeing and strengthen natural systems. Suitable materials and products, and designing with nature, support occupant comfort and reduce environmental harm. Creativity and innovation can contribute to achieving regenerative ambitions, enabling resource-efficient solutions. Monitoring performance and controlling users' satisfaction is also advisable, ensuring operational transparency.

Although presented as separate regenerative elements, the pillars and attributes function interdependently. System-based considerations reinforce place-based attributes, and human-factor elements appear in both System-based and Positive-oriented pillars, stressing the need for a holistic vision. The framework can help define criteria for regenerative action on existing buildings, acting as a structured basis for integrating regenerative ambitions in evaluations, through integration within instruments used by practitioners for assessments. Once the right elements are identified, for implementation in practice, suitable metrics and indicators must be developed [7] to assess the attributes and support decision-making.

3 Instruments Supporting the Practical Application of the Regenerative Framework

3.1 Institutional Instruments for Sustainability Evaluation

Institutional instruments such as codes, standards, regulations, and strategies have enormous influence because they set minimum requirements and shape practice. They hold significant potential for incorporating more ambitious targets toward a regenerative built environment. European standards developed by CEN/TC 350, such as prEN 15978 [11],

have developed building sustainability assessment methodologies from a life-cycle perspective. Standards such as ISO 15392:2019 [12] adopted closely aligned restorative and regenerative concepts to support sustainability targets. Reed et al. [13] highlighted the relevance of a widely accepted certification system, which draws attention to the tool Level(s), linked with the EN standards and with the support of EU policymakers.

Level(s) is a voluntary reporting tool that promotes harmonisation to set a common sustainability language [14], offering guidance for assessing and improving buildings. Level(s) encourages staged building renovation through three levels of detail [15]. It also promotes life cycle performance thinking compatible with regenerative approaches. Given its institutional status and its integration of sustainability, circularity, and quality-of-life aspects, Level(s) may become a driver of regenerative practice. However, since Level(s) does not distinguish between new and existing buildings, it may replicate limitations noted in SCSs [5] when it is applied in buildings in use. Developing a specific scheme for existing buildings, aligned with the regenerative framework here proposed, could address this gap.

3.2 Sustainability Certification Systems and Regenerative-Oriented Tools

Sustainability Certification Systems (SCSs) stand out as the most mature and recognised assessment instruments. BREEAM and LEED certification, launched in 1990 and 2000 respectively, remain the most internationally widespread [16]. The number of SCSs and scheme updates is still growing, some of them specifically directed to existing buildings, to certificate their operation or renovation. However, the schemes adaptation from new buildings to the specific features of existing ones is still limited [5]. Consequently, SCSs in existing buildings, whose performance evaluations are more complex, remain underutilised.

SCSs have been instrumental in mainstreaming sustainable building practices [6] but their focus on reducing negative impacts rather than generating positive ones [7] limits alignment with regenerative approaches. At present, the Living Building Challenge (LBC), launched in 2006 by the International Living Future Institute, is considered the SCS closest to a regenerative perspective [17]. Still, circularity issues remain at an early stage of integration [18] in SCSs as does a deeper understanding of interactions between buildings in use and their surrounding environment. Besides, some emerging instruments adopt promising approaches to regenerative sustainability. Apart from the well-known WELL Building Standard, these include The Natural Step, One Planet Living, and Planet Mark [19], and more regenerative-oriented tools, such as REGEN, Eco-Balance planning and design, Perkins + Will's framework, and LENSES framework [4]. More recently, RELi rating system has been developed for assessing and planning buildings to be resilient.

While these methods embed regenerative ideas to varying degrees, none fully assess the regenerative capacity of buildings, let alone that of existing ones. Moreover, most of them are quite experimental or are not widely applied in practice. The LENSES framework appears to be the initiative that most clearly incorporates regenerative principles. It was developed for practitioners to guide decision-making, rather than to certify the final product, promoting design measures that enhance system interconnections to create regenerative places [20]. The REGEN tool and RELi certification are remarkable for

being promoted by the USGBC (LEED certification administrator). REGEN sought to complement LEED by guiding the attainment of positive outcomes [4], but its limited metrics hindered adoption. RELi rating system [21], adopted later (in 2017) by USGBC, builds on LEED to promote resilience to climate-related impacts, expecting to become a leading system for designing communities, buildings and infrastructure adapted to unexpected events.

Leveraging the maturity of existing SCSs, complemented with insights from pioneering approaches, the next step should focus on strengthening the alignment of evaluation instruments with regenerative perspective by introducing the elements of the regenerative framework proposed for existing buildings. These tailored instruments would support the broader regenerative transformation of the building stock and contribute to climate commitments.

4 Conclusions

With a special focus on supporting the transition to achieve regenerative outcomes, this study provides a framework tailored to existing buildings. This regenerative framework is shaped by the main ambitions identified, structured through three pillars—Place-based (Pb), System-based (Sb), and Positive-oriented (Po)— and nine attributes that articulate the pillars (three in each): Building pre-conditions, Site usage patterns, and Location sensitivity (Pb-1,2 & 3); Long-term vision, Closed-looped systems, and Lasting value (Sb-1,2 & 3); Empathy with occupants; Responsible and nature-based elements, and Creativity and Innovation (Po-1,2 & 3). The hierarchical structure aims to enable practical application and support coherent assessments and decision-making.

The proposed framework is a conceptual approach that provides a structured basis for advancing regenerative transformation in existing buildings. The framework requires future validation through practical applications. Its implementation would require integrating regenerative criteria into evaluation processes and progressively aligning current assessment instruments with regenerative ambitions. In this sense, the framework represents an initial step towards the integration of regenerative principles into evaluation and decision-making processes.

The building stock must go beyond sustainability to face upcoming challenges, and the regenerative paradigm offers a promising approach. Buildings managed, operated and renovated according to the regenerative ambitions identified and outlined in the regenerative framework proposed—that is, ‘regenerative buildings’—could enhance quality of life, achieving positive impacts on both the built and natural environment.

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A Study on the Circular Management of Construction and Demolition Waste (CDW) in Türkiye

Ensar Ömer Çetin[1] and Edip Avşar[2](✉)

[1] Mir Engineering Environmental Consultancy, Ankara, Türkiye
[2] Bilecik Şeyh Edebali University, Bilecik, Türkiye
edipavsar81@gmail.com

Abstract. Rapid urbanization, urban transformation, and high seismic activity in Türkiye significantly increase the generation of construction and demolition waste (CDW), particularly after large-scale disasters like the 6 February, 2023 earthquakes. This study evaluates the circular management and recovery potential of CDW in accordance with the waste management hierarchy. Methodologically, empirical field data were collected during the source-separated demolition of a representative five-storey building (1,000 m^2) in Kahramanmaraş province. The demolition yielded approximately 134.4 tons of recoverable materials. Extrapolating these findings to the 36,932 buildings collapsed during the 2023 disaster indicates a national recovery potential of approximately 5 million tons of CDW. The study examines recycling concrete, brick, and ceramic waste into secondary aggregates, alongside recovering ferrous and precious metals (iron-steel, copper, aluminum) within a circular economy framework. Based on current market prices, a simplified economic analysis estimates the total value of these recoverable materials to range between 130 and 140 billion TL (approximately 2.5–2.7 billion euros). Ultimately, integrating post-disaster CDW into sustainable recovery processes is vital for conserving natural resources, reducing energy consumption, mitigating carbon emissions, and enhancing economic sustainability.

Keywords: Construction and Demolition Waste · Waste Management · Resource Recovery · Circular Economy · Disaster Waste · Sustainability

1 Introduction

Technological advancements and changing living standards have had a significant impact on urban development, as in many other fields. The construction of high-rise buildings, the renewal of asphalt roads, and the restoration of residential buildings have been accompanied by a substantial increase in waste generation. Over the past century, the construction sector in Türkiye has undergone a remarkable expansion. The gross domestic product (GDP) derived from the construction sector increased from 33.6 billion TL in the second quarter of 2025 to 36.7 billion TL in the third quarter of 2025. Between 1995 and 2025, the average GDP generated by the construction sector amounted to 18.8 billion

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TL, reaching its highest level of 36.7 billion TL in the third quarter of 2025 (Trading Economics, 2025). According to the Construction Production Index data published by TÜİK for October 2025 (with 2021 as the base year = 100), the building construction sub-sector index increased by 28.8% compared to the same month of the previous year, while the non-building construction sub-sector index rose by 21.8%, and the specialized construction activities index increased by 29.9%. These data clearly demonstrate the critical importance of the construction sector for the Turkish economy (TUİK, 2025).

In such a rapidly growing sector, the supply of raw materials is of critical importance. Concrete and metals constitute the fundamental building blocks of the construction industry. In addition to these materials, a significant amount of recyclable waste is generated during the demolition phase of buildings. The natural disaster that occurred in Türkiye on 6 February 2023, for which a Level 4 earthquake alert was issued, affected an area of approximately 120,000 km^2. Within this region, where nearly 15 million people reside, demolition activities took place across 11 provinces, 124 districts, and 6,929 villages and neighborhoods. As a result of the earthquakes, 36,932 buildings collapsed at the time of the event, while an additional 311,000 buildings—comprising a total of 872,000 independent units—became uninhabitable due to severe structural damage. The number of buildings that collapsed by province is presented in Table 1. (TMMOB, 2023).

Table 1. Number of Buildings Collapsed in Earthquake-Affected Provinces

No	Earthquake-affected provinces	Number of collapsed buildings
1	Adana	88
2	Adıyaman	5,826
3	Diyarbakır	21
4	Elâzığ	56
5	Gaziantep	3,783
6	Kahramanmaraş	7,307
7	Malatya	4,238
8	Hatay	13,883
9	Kilis	448
10	Osmaniye	649
11	Şanlıurfa	633
	Total	**36,932**

This table demonstrates that Türkiye is a seismically active country and that pre-disaster risk management is an essential component of damage mitigation that must not be overlooked. It also highlights the significant scale of the construction sector in Türkiye within the context of crisis management. In addition, the large volume of construction and demolition waste generated as a result of such disasters should not be ignored, and these wastes should be incorporated into circular management and recovery processes. The processes of constructing, renovating, and demolishing buildings give rise to construction

and demolition waste consisting of a complex mixture of various material types. These wastes are generally classified as inert waste (such as sand, brick, and concrete) and non-inert waste (including plastic, paper, glass, wood, vegetation, and other organic materials) (Ulubeyli et al., 2017). While a portion of this waste can be recycled, others cannot be recovered. Among these waste fractions, concrete and iron constitute the largest proportions. In Türkiye, the management of construction and demolition waste is regulated under the Regulation on General Principles of Waste Management, and the waste types listed in Annex IV of the regulation. (ÇŞB, 2008). Therefore, the primary objective of this study is to quantify the recovery potential of CDW generated by the 6 February 2023 earthquakes and to evaluate its economic and environmental value within the framework of a circular economy. By analyzing empirical data from a representative demolished building, this study aims to provide actionable insights and a macro-level baseline for post-disaster waste management strategies.

2 Materials and Methods

Within the scope of this study, a five-storey building with a total floor area of 1,000 m^2 that was demolished in Kahramanmaraş province following the 6 February 2023 earthquake was selected as a case study. To obtain robust waste generation data, the demolition process was continuously monitored by an environmental engineer. Instead of visual estimation, the quantification of waste was conducted through direct measurement. During the demolition, materials were classified and separated on-site. The separated CDW fractions were then loaded onto transport trucks, and their precise net weights were recorded using industrial weighbridges before being transferred to licensed recovery facilities.

3 Results

As a result of the field study, the materials obtained from construction and demolition waste (CDW) generated during the demolition of the sample building and classified according to their types are presented in Table 2. All of these wastes were transferred to licensed recovery companies for evaluation, and efforts were made to minimize waste through sustainable management practices. In addition, among the remaining waste fractions, those classified under waste code 17 01 07 (mixtures of concrete, brick, tiles, and ceramics) were also included in the recovery process by being utilized as aggregates.

Aggregates constitute a critical input in concrete production, accounting for approximately 75% of the total concrete volume. However, on a global scale, only about 18% of the aggregates produced are obtained through recycling from waste materials such as industrial waste, ash, and slag (URL, 1, 2023). In Türkiye, it is estimated that approximately 200 million tons of aggregate are required annually for the production of around 110 million m^3 of ready-mixed concrete, based on an average requirement of 1.8–2.0 tons of aggregate per cubic meter of concrete (THHB, 2013). The extraction and processing of these materials from natural sources exert significant environmental impacts.

Under current conditions, natural aggregates are predominantly used in concrete production. Since these materials cannot be reused after consumption, substantial economic costs arise at both the production and consumption stages, along with considerable environmental challenges. Practices aimed at the recycling of construction and demolition waste (CDW) were first implemented in the 1970s in certain regions of the United States and Europe due to the depletion of natural resources used in concrete production. During the 1980s, the establishment of separation and recycling facilities accelerated as a result of limited landfill capacity, environmental problems caused by construction and demolition waste, and increasing environmental awareness regarding raw material consumption. Today, the most commonly applied disposal method in the management of construction and demolition waste is recycling, followed respectively by incineration and landfilling. In European Union countries, practices related to the recycling of construction and demolition waste began in the 1990s, while in Türkiye the first recycling facility for these wastes became operational in 2006 (Ulubeyli et al., 2017).

Table 2. Amounts of Recyclable Materials Obtained from the Demolition of a Building with a Total Floor Area of 1,000 m^2

Waste type	Amount (kg)	Description
Plastic	3,000	Pipes, some interior coverings
PVC	26,000	Doors and windows
Iron and steel	90,000	Columns, beams, and slab reinforcements
Fixtures (brass)	300	Bathroom and kitchen sources
Fixtures (copper)	400	Bathroom and kitchen sources
Mixed cables	2,500	Electrical, plumbing, and antenna connections
Glass	2,200	Windows and other glass components
Wood	2,000	Doors, cabinets, parquet flooring, and windows
Aluminum	2,000	Door and window frames
Copper	6,000	Electrical installations
Total	**134,400**	

Construction and demolition waste that is not contaminated with hazardous substances have the potential to be fully recovered. The recovery of these wastes contributes to the conservation of natural resources while also reducing waste disposal costs (Eren and Şen, 2023). Across European Union member states, the average annual generation of construction and demolition waste per country is approximately 20.2 million tons, with an average recovery rate of about 49.4% (Vieira, 2015). Materials recycled from construction and demolition waste (CDW) are processed in accordance with relevant technical standards by companies licensed by the Ministry of Environment, Urbanization and Climate Change, and are subsequently used either alone or in combination with natural aggregates in concrete production, road and pavement construction, drainage applications, and infrastructure and superstructure projects (Eren and Şen, 2023). The

reuse of materials obtained through the recovery process is of great importance from both economic and environmental perspectives. The utilization of these materials as secondary raw materials not only contributes to the conservation and sustainable management of natural resources but also provides significant benefits in terms of human health and environmental protection. Within the waste management hierarchy, when the prevention or reduction of waste generation—the highest priority—cannot be achieved, reuse or recycling represents the most effective management option for construction and demolition waste (EC, 2020).

Recovery of Concrete Materials: Concrete waste separated from construction and demolition waste (CDW) is transported to recovery facilities. Upon arrival at the facility, the incoming waste is recorded in the automation system and then subjected to crushing by being fed into a primary crusher. Subsequently, the material is further reduced in size using a jaw crusher and conveyed to screening units via conveyor belts. The screened materials are passed through a magnetic separator to remove any remaining metal content. The resulting materials are then classified according to sieve sizes, and the aggregates prepared for shipment are stored in separate areas using conveyor systems. The recovered aggregates can be used not only in concrete production but also as fill material in new construction sites, road works, and various applications requiring ground filling (Poon et al., 2001). A schematic diagram of the process is presented in Fig. 1.

Recycling of Plastic Materials (Clean and Contaminated): Plastic waste is accepted at licensed recovery facilities. The received plastics are subjected to a shredding process using crushers and reduced to the desired particle sizes. The shredded plastics are then transferred to washing tanks to remove impurities adhering to their surfaces. During this stage, the waste is washed and purified from contaminants. The cleaned and dried plastics are subsequently conveyed to the granulation line, where they are melted through thermal processing and formed into strands. These strands are cooled in a water bath and then transferred to the cutting line, where they are cut into granules of the required size using appropriate blades, thereby converting them into secondary raw materials (Fig. 2). These raw materials can be utilized in various sectors depending on market demand, including textiles, agriculture, industrial and technical products, as well as a wide range of materials commonly used in daily life (Hopewell et al., 2009).

Recycling of Ferrous Materials: During the initial stage of demolition, iron materials originating from the reinforcement of columns, beams, and slabs are separated on-site. The separated ferrous materials are transported to metal recovery facilities together with the iron obtained through magnetic separation during the aggregate recovery process from concrete waste. At the facility, following size reduction processes, the materials are melted in high-temperature furnaces and cast into molds to obtain products in the desired form. Metals can be recycled indefinitely through this process (Reuter et al., 2013). The recycling process of ferrous materials is presented in Fig. 3.

Recycling of Glass Materials: Glass waste collected during the demolition process is transported to recovery facilities, where it is sorted according to color. The sorted glass waste is then crushed in milling machines to reduce particle size and completely remove impurities. Subsequently, the material is melted in furnaces at temperatures ranging

between 1,400 and 1,600 °C, shaped, and prepared for market distribution (Fig. 4). Glass waste derived from construction and demolition activities is primarily used in the production of glass wool insulation materials or as an additive in asphalt pavements during road construction. Since glass is a material that can be recycled indefinitely, it plays a significant role in promoting environmental sustainability. Glass recycling not only reduces raw material consumption but also leads to substantial reductions in carbon emissions and energy use (Corinaldesi et al., 2005).

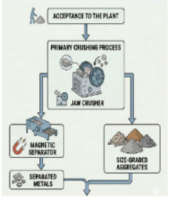


Fig. 1. Schematic representation of the concrete recovery process

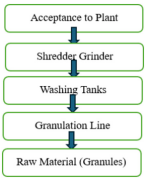


Fig. 2. Schematic representation of plastic materials recycling process

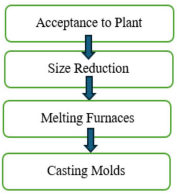


Fig. 3. Schematic representation of ferrous materials recycling process

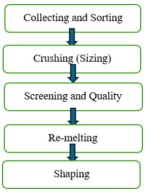


Fig. 4. Schematic representation of glass materials recycling process

Recycling of Precious Metals (Aluminum, Copper, etc.) Precious metals recovered from construction and demolition waste are first subjected to a classification process. During this stage, metals such as copper, aluminum, and brass are separated by type, cleaned, and reduced into smaller pieces. These metals are primarily obtained from bathroom and kitchen fixtures, doors and windows, and electrical installations. After sufficient size reduction, the precious metals are transferred to melting furnaces, where they are converted into a molten state through thermal processing. The molten material is then poured into casting molds to obtain products in the desired form. In some cases, complex mixed wastes may also undergo additional separation using electrolysis tanks. The recovery of precious metals not only contributes to the conservation of natural resources but also significantly reduces energy consumption. Due to their high economic value, the recovery of these metals represents a substantial economic benefit (Reuter et al., 2013). The precious metal recovery process is illustrated in Fig. 5.



Fig. 5. Schematic representation of precious metals recycling process

4 Discussion

The field data demonstrate that construction and demolition waste (CDW) possesses substantial recovery potential. Reusing inert materials, such as concrete, brick, and ceramics, as aggregates conserves natural resources and mitigates the environmental impacts of mining. Furthermore, recovering recyclables like iron, aluminum, copper, glass, and plastics provides significant environmental and economic benefits. This process reduces landfill requirements, saves energy, and lowers carbon emissions, strongly supporting circular economy principles.

Empirical findings show that approximately 134.4 tons of recoverable CDW can be separated from a representative 1,000 m^2 five-storey building. Extrapolating this to the 36,932 buildings collapsed during the 6 February 2023 earthquakes yields a national estimate of roughly 5 million tons of recoverable waste.

The economic potential of these materials is immense. A simplified market valuation estimates the value of iron/steel scrap at approximately 79 billion TL, plastics at 33.6 billion TL, copper at 15.5 billion TL, aluminum at 3.3 billion TL, and other wastes at 1–2 billion TL. Overall, the total economic value is projected to reach 130–140 billion TL (2.5–2.7 billion euros). These findings confirm that effective CDW recovery delivers substantial economic gains alongside environmental benefits.

Importantly, this economic valuation is strictly based on average domestic secondary raw material and scrap market prices valid in the final quarter of 2023, with conversions relying on the average exchange rate of that period. These estimated figures represent gross potential revenue; operational expenses, including demolition, separation labor, transportation, and metallurgical processing costs 4were excluded from this calculation.

5 Conclusion

In conclusion, the effective management of construction and demolition waste is of critical importance not only for environmental protection but also for economic sustainability and resource efficiency. In accordance with the waste management hierarchy, when the prevention of waste generation cannot be achieved, the widespread implementation of reuse and recycling practices becomes essential. In this context, supporting licensed recovery facilities, increasing on-site separation practices, and ensuring the effective enforcement of regulations are of paramount importance. The adoption of recovery-oriented approaches within the construction sector will contribute to the conservation of limited natural resources and promote more sustainable urban development.

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Cold Plasma for Safe and Circular Water Reuse in the Built Environment

José Gonçalves[1(✉)], Tom Koritnik[2], João Pequeno[1], Joana Antunes[1], Israel Diaz[3], Jure Zigon[4], and Davor Krzisnik[3]

[1] MARE - Marine and Environmental Sciences Centre, ARNET - Aquatic Research Network Associate Laboratory, and Department of Applied Social Sciences, NOVA School of Science and Technology, NOVA University Lisbon, Caparica, Portugal
jose.goncalves@fct.unl.pt

[2] Department for Public Health Microbiology, National Laboratory of Health, Environment and Food, Ljubljana, Slovenia

[3] Institute of Sustainable Processes, University of Valladolid, Valladolid, Spain

[4] Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia

Abstract. Cold plasma (CP) is emerging as a promising advanced oxidation technology for decentralized water disinfection, offering broad-spectrum antimicrobial potential, low energy demand and minimal chemical residuals. In the context of circular and resilient urban water systems, a key challenge is to move beyond millilitre-scale laboratory reactors towards scalable units that can be integrated into building and district water loops. This work presents the conception and proof-of-concept evaluation of a dielectric barrier discharge (DBD) cold-plasma reactor equipped with a microbubble diffuser, specifically designed to enhance gas-liquid interaction and enable modular upscaling for the built environment. The prototype allows treatment of 500 mL water volumes, representing a substantial increase compared with conventional benchtop configurations, and is validated using *Escherichia coli* as a representative fecal indicator organism. The reactor ensures stable discharge and reproducible antimicrobial performance, achieving multi-log reductions in colony-forming units within treatment times compatible with on-site or point-of-use sanitation. Design choices are discussed in terms of footprint, energy efficiency and potential integration in greywater reuse systems and high-risk building effluents. The reactor concept provides a flexible platform for future assessment of clinically relevant pathogens, antibiotic residues and microplastics-associated contaminants, contributing to safer water reuse streams and to reshaping the built environment through sustainability and circularity.

Keywords: cold plasma · water disinfection · antimicrobial resistance · water re-use · circular water systems

1 Introduction

The transition towards circular, healthy and resilient cities requires closing water loops while guaranteeing microbiological safety and controlling emerging contaminants such as pharmaceuticals and antibiotic resistance determinants [1]. Urban water reuse schemes

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at building and district scales are increasingly promoted to reduce potable water demand and augment local water resilience, yet conventional disinfection processes often rely on chemicals that generate disinfection by-products and require complex dosing and storage infrastructure. These constraints are particularly problematic in decentralized or small-scale systems, such as greywater reuse in buildings, hospital effluent polishing or emergency water supply, where compact, low-chemical and easily automatable solutions are needed [2–4].

Cold atmospheric plasma (CAP) has gained attention as an advanced oxidation and disinfection technology capable of generating reactive oxygen and nitrogen species, UV photons and transient electric fields directly in water or at gas-liquid interfaces [5, 6]. Numerous studies have demonstrated efficient inactivation of *Escherichia coli* and other pathogens in small-volume systems, including dielectric barrier discharge (DBD) reactors, plasma jets and plasma sparks, often achieving several-log reductions within minutes [7–9]. Plasma-activated water (PAW), where water is exposed to CAP and subsequently used as a disinfectant, has also been proposed as a versatile antimicrobial solution for sanitation and cleaning [10, 11]. However, most experimental configurations treat volumes in the microlitre-to-millilitre range or rely on batch activation of a few hundred millilitres, which limits direct translation to flow-through units compatible with building-scale water flows [6].

Improving plasma-liquid mass transfer is a critical step towards scalable water treatment reactors. Recent work has shown that integrating microbubble generation with CAP can significantly enhance gas-liquid contact area and increase the transport of reactive species into the bulk liquid, thereby accelerating microbial inactivation [12, 13]. At the same time, there is growing interest in plug-and-play plasma modules that could be integrated into decentralized water infrastructures, emphasizing compact form factors, modular design and compatibility with existing hydraulic layouts [14, 15].

The present study addresses these gaps by developing and testing a bubble-enhanced DBD reactor designed for integration in circular water systems within the built environment. *E. coli* is used as a model fecal indicator microorganism to characterize reactor performance and assess the feasibility of achieving rapid and reproducible inactivation at a 500 mL scale. The work focuses on reactor conception, operating conditions relevant for on-site applications, and comparison with a reference microvolume CP treatment, rather than on detailed mechanistic analysis or extended pathogen panels, which are reserved for future studies.

2 Materials and Methods

2.1 Reactor Design and Configuration

A cylindrical dielectric barrier discharge reactor was constructed to enable treatment of 500 mL water volumes in batch mode (continuous operation is feasible but was not evaluated in this study). The reactor consisted of a quartz tube acting as the dielectric barrier, with a coaxial electrode configuration comprising an inner stainless-steel rod electrode and a copper electrode wrapped around the outer surface of the tube. The inter-electrode distance was defined by the quartz wall thickness and reactor geometry, ensuring stable discharge under atmospheric conditions.

The reactor configuration was selected following preliminary testing of different dielectric materials (PVC, borosilicate glass, quartz) and electrode geometries (rod, screw-type inner electrodes; linear and helical outer electrodes), with quartz and coaxial rod-cylinder configuration providing the most stable discharge, lowest current variability, and minimal thermal effects during operation. Reactor temperature was monitored during operation using an infrared thermometer to confirm non-thermal conditions.

For indirect plasma treatment, a bubble diffuser (with a diameter of 10 cm) was installed at the bottom of the reactor and connected to a compressed air supply via a flow regulator. The diffuser generated fine bubbles (with a diameter of ≈100–400 μm) that traversed the liquid column, enhancing gas-liquid interfacial area and promoting the transfer of plasma-generated RONS into the bulk liquid. The gas flow rate was fixed at 2 L min^{-1} for all experiments, based on preliminary optimization showing stable discharge and consistent physicochemical conditions.

Cold plasma was generated in atmospheric air using a custom-built high-voltage alternating current power supply operated at 15 kV and 5 kHz. Under these conditions, the discharge current was approximately 2.3 mA, corresponding to an input power of ~34.5 W. Voltage and current waveforms were monitored using a high-voltage probe and current sensor connected to an oscilloscope to ensure stable plasma generation throughout the experiments.

Based on these operating conditions, the specific energy input for a 30 min treatment of 500 mL was approximately 124 kJ L^{-1}, providing a preliminary estimate of the energy demand of the system under proof-of-concept conditions.

2.2 Culture Conditions

Escherichia coli (strain ATCC25922) was selected as a representative fecal indicator organism and model pathogen widely used in plasma disinfection research. Overnight cultures were grown in LB nutrient media at 37 °C.

For each experimental run, 500 mL of sterile distilled water was spiked with an *E. coli* suspension prepared from overnight LB cultures; cells were concentrated by centrifugation (4,000 × g, 5 min), washed three times in sterile PBS and resuspended to the target density. Suspensions were adjusted by OD_{600} using a standard curve and confirmed by serial dilution and plating, achieving an initial challenge concentration of approximately 1 × 10^7 CFU·mL^{-1}.

The gas flow rate applied voltage and treatment duration were set according to the operating conditions selected for proof-of-concept evaluation and with lowest power input where plasma was stable (15 kV and 2.3 mA). After plasma exposure, aliquots were immediately collected, serially diluted and plated withoit neutralization on blood agar to determine surviving colony-forming units (CFU). Plates were incubated at 37 °C for 24 h before enumeration. Parallel aliquots were measured by OD*600* before plating preparation and showed no appreciable change, indicating minimal loss during sample processing.

2.3 Experimental Design and Sampling

Inactivation experiments in the 500 mL reactor were conducted in triplicate. Sampling times were selected to capture the early, intermediate and advanced stages of inactivation, with measurements at 0 (untreated control), 10, 20, 30, 45 and 60 min. At each time point, aliquots were withdrawn aseptically from the reactor, neutralized if necessary to quench residual reactive species, and processed for CFU enumeration. Cold plasma was applied during the first 30 min, followed by 30 min of post-treatment without discharge to assess the residual disinfection potential of plasma-generated species.

Bacterial inactivation was expressed as percentage of surviving bacteria relative to the initial concentration at time zero and as inactivation rate (percentage reduction). Triplicate measurements were used to compute mean values and standard deviations for each time point. Inactivation curves were plotted as survival fraction versus exposure time, and error bars reflected variability between replicates.

3 Results and Discussion

The DBD source coupled to the air diffuser produced a homogeneous discharge in the gas phase, and the resulting plasma-activated air was continuously bubbled into the 500 mL water volume (Future 1). The discharge remained stable over the full 30 min treatment in all three replicates, with no arcing or hot spots, consistent with indirect CAP configurations where RONS generated in the gas phase are transferred into the liquid via bubbling (Fig. 1) [12].

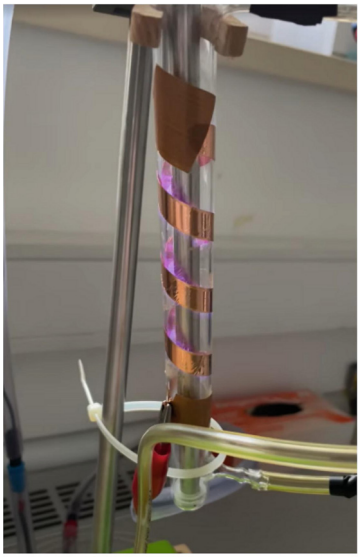


Fig. 1. Dielectric barrier discharge (DBD) source coupled to the air diffuser, showing a stable, homogeneous and continuous cold plasma discharge in the gas phase of the reactor.

The gas flow rate was fixed at 2 L/min, providing intense but well-controlled bubbling that delivered plasma-generated species without excessive splashing or droplet entrainment into the discharge region. Under these conditions, bulk liquid heating was limited and the process remained clearly non-thermal, in line with other plasma-activated water systems.

Mean initial concentration across the three replicates was 4.96×10^8 CFU 100 mL^{-1} ($\pm 6.30 \times 10^7$). After 30 min of exposure the mean concentration fell to 1.27×10^8 CFU 100 mL^{-1} ($\pm 7.49 \times 10^7$), corresponding to a 74.4% reduction and a $\log_{10}$ reduction of 0.59. At 45 min the mean CFU was 4.35×10^6 CFU 100 mL^{-1} ($\pm 1.10 \times 10^5$), representing a 99.12% reduction and a log reduction of 2.06. After 60 min (30 min post-treatment) the mean CFU reached 2.08×10^6 CFU 100 mL^{-1} ($\pm 2.08 \times 10^5$), corresponding to a 99.58% reduction and an log reduction of 2.38. Error bars in Fig. 2 represent ±SD.

This behaviour supports the hypothesis that efficient gas–liquid transfer of plasma-generated RONS enables effective treatment of larger volumes by distributing these species throughout the bulk liquid [7, 13].

From a built-environment perspective, the ability to achieve nearly complete inactivation in a 500 mL batch using an indirect, air-fed system suggests that bubble-assisted plasma modules could be scaled as side-stream units for small storage tanks, flush reservoirs or other building-level disinfection points, without the need for chemical dosing.

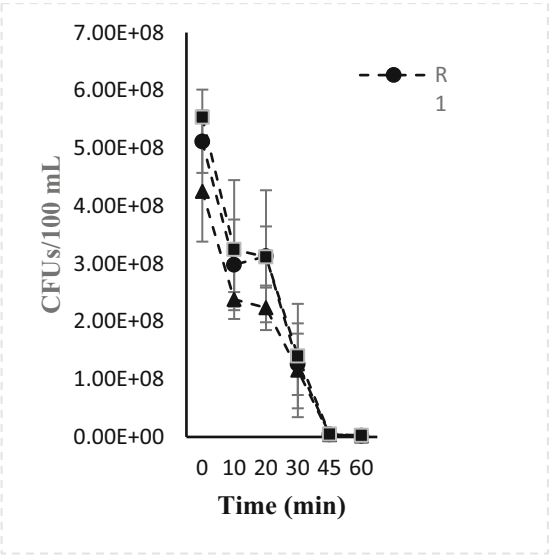


Fig. 2. Inactivation of *E. coli* in the laboratory-scale bubble-assisted DBD reactor: temporal evolution of CFU/100 mL over 60 min for three independent replicates (R1–R3), showing progressive reduction to below the detection limit.

By relying on plasma-activated air and long-lived RONS rather than stored chemical disinfectants, bubble-assisted DBD modules have potential as compact side-stream polishing units for building tanks or reservoirs; however, this study tested only distilled water in batch mode and therefore provides proof-of-concept rather than validated field performance. The present results demonstrate that plasma-derived species can persist and contribute to extended microbial inactivation in a simple water matrix, but the efficacy and kinetics observed here will likely change in complex waters due to oxidant demand, particulate shielding and variable ionic strength.

Accordingly, broader applications such as greywater tanks, rainwater cisterns, hospital effluent polishing should be considered as future directions rather than immediate outcomes. Key next steps include testing under realistic matrices (representative greywater and hospital effluent), evaluating the impact of organic load and turbidity on RONS lifetime and transfer, assessing virus and protozoan susceptibility, and performing continuous-flow and scaled side-stream experiments to confirm hydraulic compatibility and treatment throughput. Energy and life-cycle assessments should also be undertaken to compare the modules with established decentralized treatments and to quantify environmental trade-offs.

These targeted limitations and follow-up experiments will better position the reactor concept for translation into circular built-environment applications while preventing overinterpretation of the current laboratory-scale findings.

4 Conclusions

The laboratory-scale, bubble-assisted DBD reactor operating in indirect mode was successfully demonstrated as a compact disinfection unit suitable for integration in the built environment. Using *E. coli* as a model organism, the system achieved 73.31% inactivation after 30 min of plasma exposure and 99.58% after an additional 30 min without active discharge, confirming the strong and persistent antimicrobial effect of long-lived plasma-generated species in the treated water. These results suggest that efficient transfer of reactive oxygen and nitrogen species from plasma-activated air into water can provide robust microbial control at volumes relevant for building-scale storage and reuse. The laboratory findings therefore indicate that similar bubble-assisted plasma modules could be developed as decentralized, low-chemical disinfection blocks for circular water systems, supporting safe greywater and rainwater reuse while reducing reliance on centralized treatment and conventional disinfectants. However, this is a very preliminary study. Other bacteria, viruses, should be evaluated as well as antibiotics and other contaminants of emerging concern. Energy efficiency needs to be explored as well as scalability potential.

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Toward a Pattern Language for Housing Rehabilitation

Eduardo Reuter Schneck[1(✉)], Andrea Parisi Kern[2], and Vinicius M. Netto[3]

[1] Universidade Feevale, Novo Hamburgo RS 93525-075, Brazil
eduardoschneck@feevale.br
[2] Universidade do Vale do Rio dos Sinos, São Leopoldo RS 93022-750, Brazil
[3] Universidade do Porto, Porto 4200-465, Portugal

Abstract. Building rehabilitation is a strategy for delivering Social Housing (SH) in consolidated urban areas, yet systematic design knowledge remains limited. This study proposes context-specific new design patterns (NPs) for SH rehabilitation, exploring how pattern languages can be empirically extended to address its challenges. We mapped the occurrence of selected patterns from Christopher Alexander's Pattern Language – originally conceived as generative elements of human-centered environments – across twenty rehabilitated buildings in Brazil and Portugal and compared them with a control sample of five peripheral projects from a Brazilian SH program. Pattern co-occurrence networks were constructed and analyzed using centrality metrics to identify structurally salient patterns and relational differences between contexts. Rehabilitated cases exhibited more integrated pattern networks, while peripheral developments showed weaker relational structures, revealing recurrent absences interpreted as "anti-patterns". Associated affordance gaps enabled the codification of twenty taxonomically structured NPs. By linking rehabilitation constraints, circular reuse of existing assets, and long-term adaptability, the study contributes preliminary design knowledge for more regenerative and context-sensitive SH rehabilitation.

Keywords: Building Rehabilitation · Design Patterns · Social Housing

1 Building Rehabilitation and Pattern Languages

Building rehabilitation has emerged as a strategic approach to delivering Social Housing (SH) in central urban areas, where infrastructure, services, and vacant building stocks are concentrated [1]. Rather than promoting peripheral expansion, it leverages existing assets and reconnects SH to established networks of mobility, employment, and amenities [2, 3]. It also operates as a circular and regenerative practice by extending building service life, reducing material consumption, and reactivating underused urban assets within consolidated urban fabrics [4]. Thus, rehabilitation must reconcile existing structural constraints with contemporary requirements and affordability demands. Unlike new construction, it cannot define spatial organization from the outset; instead, it must determine which conditions can be preserved or adapted to support habitability.

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This makes rehabilitation a productive domain for pattern-based reasoning, where patterns can be interpreted as adaptive configurations rather than generic solutions [5]. "A Pattern Language" by Christopher Alexander and his team [6] offers a generative vocabulary for coherent built form and a problem-adjacent lens to analyse how design solutions manifest, interrelate, and, at times, remain absent [5]. Comprising 253 patterns, each formulated as a context-sensitive response to recurring spatial problems [6], the framework links functional requirements to human perception and everyday use. Rather than prescribing isolated interventions, it emphasizes interdependence, with patterns operating in combination across urban, architectural, and constructive scales [5]. Alexander's later work reframes patterns as expressions of underlying forces shaping form in recurrent situations [7]. From this perspective, design is morphogenetic, emerging through context-sensitive processes rather than fixed models. These structure-preserving operations strengthen the existing whole through incremental changes that enhance its "life," assuming spatial systems are organized around interacting centers that interventions should reinforce rather than erase [7].

This adaptive logic is inseparable from the concept of "wholeness", understood as an objective structure formed by interrelated centers whose coherence determines the degree of life in a spatial system [7]. Rather than a compositional totality, it is an emergent property across scales, with patterns serving as instruments to sustain and intensify it over time. When patterns fail to maintain this integrity – due to contextual shifts, technical constraints, or changing modes of inhabitation – loss of wholeness manifests in recurrent dysfunctions of use and appropriation [7], indicating the need for new configurations capable of restoring or strengthening the system's structure [8].

An additional lens is offered by affordance theory, which refers to the action possibilities an environment offers to an organism, emerging from the relational properties between spatial form and embodied capability [9]. Although not explicitly named, descriptions of how spatial configurations invite or constrain use [7] align with this perspective. Patterns can thus be seen as arrangements that generate affordances – enabling interaction, adaptation, and appropriation without prescribing specific behaviors.

Understanding patterns through these complementary concepts has direct implications for the evolution of pattern languages. When grounded in observed forces and the affordances generated by spatial configurations, shifts in social practices, technologies, or constraints may require extending or refining the existing lexicon. Rather than a closed system, pattern languages are conceived as continuously evolving frameworks responsive to emerging conditions [6, 7, 10]. Accordingly, new patterns can be justified when evidence reveals persistent gaps not addressed by the original corpus [8, 11, 12].

Thus, patterns function as testable hypotheses about how configurations generate affordances across scales, while repeated failures to deliver expected outcomes can be read as "anti-patterns" – self-reinforcing arrangements that undermine spatial performance and social well-being, often observed in large-scale SH [13–16]. In Brazil, the Minha Casa Minha Vida Program (PMCMV) became the country's largest housing initiative; however, persistent issues include peripheral siting, limited adaptability, and weak urban integration [17, 18]. They stand in opposition to Alexander's principles which prioritize spatial adaptability, diversity, and social well-being [19].

Taken together, this literature supports deriving new patterns from convergent evidence rather than isolated criteria. In this context, this paper proposes a set of preliminary, context-specific new design patterns for SH rehabilitation.

2 Methods

This study combines empirical pattern mapping, network metrics, and affordance-based interpretation to derive anti-patterns and propose new patterns for SH rehabilitation. Figure 1 summarizes the methodological steps described in the following sections.

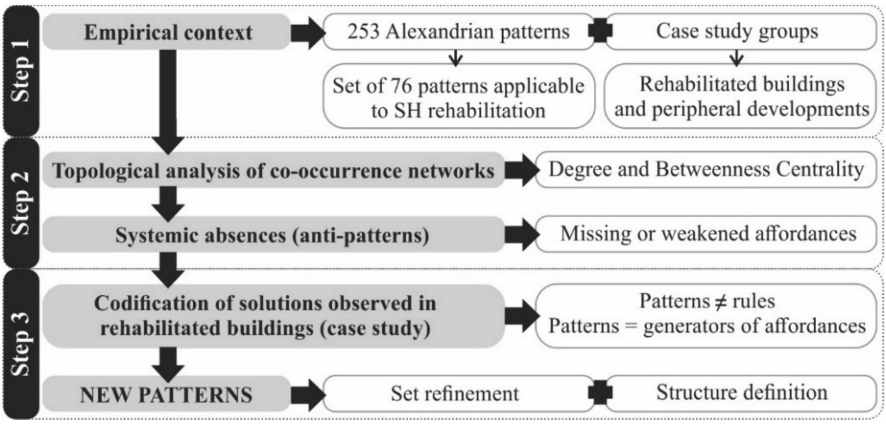


Fig. 1. New pattern derivation process.

2.1 Pattern Identification Across Case Groups

This research builds on a preliminary set of patterns identified in a previous study [16]. The 253 patterns [6] were first screened to exclude those unrelated to SH, followed by a second filter removing patterns not applicable to building rehabilitation. The resulting set was validated through a focus group [20], composed of participants with academic and professional expertise, yielding 76 patterns considered applicable to rehabilitation.

The presence of these patterns was analyzed in twenty rehabilitated buildings across Portugal and Brazil. The Portuguese cases are located in Porto, comprising buildings of three to seven floors. In Brazil, the sample includes buildings in Porto Alegre (two) and São Paulo (eight), ranging from four to twenty-three stories. Selection criteria included (i) location in dense urban areas with established infrastructure; (ii) multi-family typology with shared circulation (iii) adaptive rehabilitation of existing structures; and (iv) provision as subsidized housing. Despite scale differences, both contexts show similar housing dynamics – significant vacancy (12–13%) and deteriorated building stocks.

A control group of five peripheral multifamily developments was defined based on the Minha Casa, Minha Vida Program (PMCMV) database [21], filtering completed

Faixa 1 vertical projects with complete addresses in Porto Alegre and São Paulo. Five cases were randomly selected for exploratory comparison. To ensure comparability, five rehabilitation cases were randomly drawn from the initial twenty. In both datasets, pattern occurrence was assessed through document and drawing analysis, photographic records, and on-site observation. To make pattern identification explicit, each pattern was assessed through at least two operational questions derived from its original formulation. Figure 2 illustrates the presence of patterns and anti-patterns.

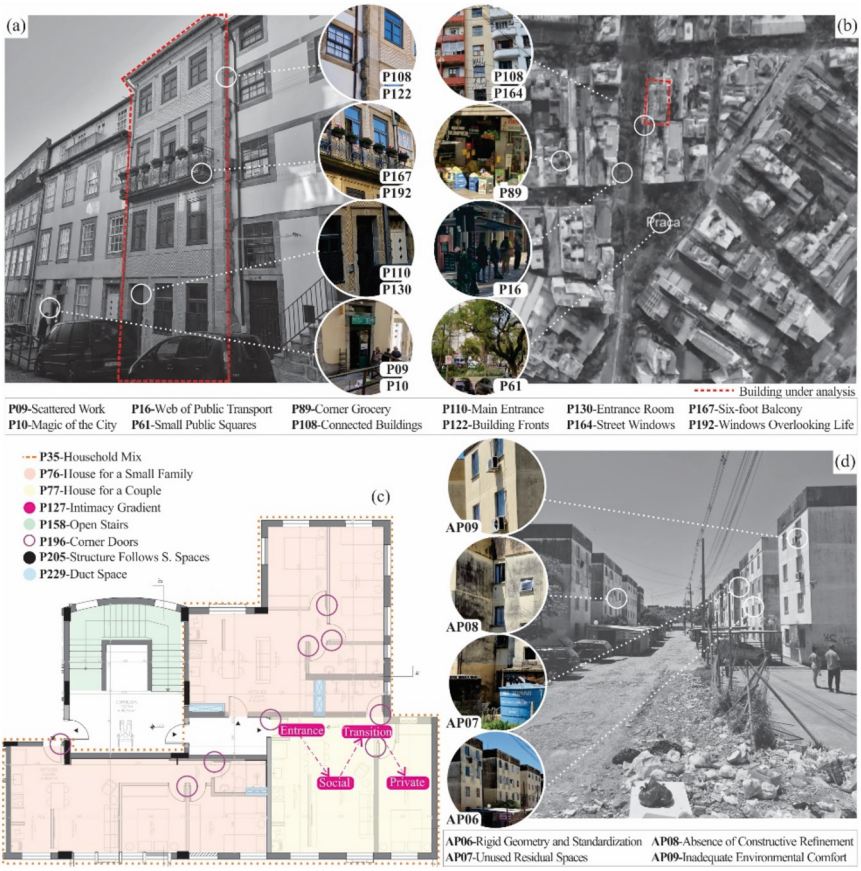


Fig. 2. Identification of design patterns in (a) a rehabilitated building; (b) its immediate surroundings; and (c) floor plan; identification of (d) anti-patterns in a peripheral development.

2.2 Research Step 2: Deriving Anti-patterns from Network Evidence

Co-occurrence (CO) matrices were constructed to quantify how often pairs of patterns appeared together across cases, including both the rehabilitated corpus and a control group of five peripheral buildings. These matrices were converted into CO networks,

with patterns as nodes and CO as edges. Two centrality measures were applied to identify structurally salient patterns [22]: Degree Centrality (DC), representing overall connectedness, and Betweenness Centrality (BC), indicating bridging roles between groups. To compare networks of different sizes, DC was normalized as DC/(n−1).

Anti-patterns were derived by comparing two networks: the peripheral SH sample and a subset of five rehabilitated buildings. DC, BC, and network density were examined to characterize each relational structure. The rehabilitated network, with higher density and stronger interdependencies, served as an empirical baseline. Anti-pattern evidence was defined by the consistent absence, isolation, or weak connectivity of structurally significant baseline patterns in the peripheral network.

2.3 Research Step 3: Deriving NPs from Anti-pattern-Based Affordance Gaps

For each anti-pattern, a corresponding affordance gap was defined as an expected action possibility in everyday habitation that is systematically unsupported. Design responses observed in rehabilitated buildings that countered these conditions were translated into affordances and treated as generative strategies for new patterns (NPs). At this stage, validation was internal and procedural rather than post-occupancy based. Each NP was checked against three criteria: (i) derivation from an identified anti-pattern or affordance gap; (ii) correspondence with a design response observed in the rehabilitation cases; and (iii) non-duplication of an existing pattern [6]. Each NP followed a taxonomic structure comprising: Problem, Discussion, Solution and Graphic scheme.

3 Results and Discussion

Step 1 produced a binary dataset recording pattern occurrence across (i) 20 rehabilitated buildings in Portugal and Brazil and (ii) five peripheral PMCMV developments. For comparability, five rehabilitation cases were randomly selected to match the control sample. Of the 76 patterns, 48 were identified in the rehabilitated subset and 21 in the peripheral developments. CO matrices were then constructed for the matched 5-case subsets and the full 20-building corpus to capture pattern interdependence. These were converted to .json network format and analyzed in VOSviewer to compute network metrics and support inspection (Table 1).

Table 1. Dataset and derived network summary.

Dataset	Cases (n)	Patterns as nodes	Links (n)	Density
Rehabilitation baseline (random subset)	5	48	1053	0.934
Peripheral PMCMV control	5	21	178	0.848

When compared, the peripheral network shows fewer patterns (21 vs. 48) and far fewer links (178 vs. 1053), indicating more limited combinations. Table 2 compares the seven most connected baseline patterns and their roles in the peripheral network.

Table 2. Baseline-salient patterns and their reduced DC/BC roles in the peripheral network.

Pattern	REHAB baseline			PMCMV control		
	DC	normDC	BC	DC	normDC	BC
P09-Scattered Work	47	1.000	0,000249	14	0.700	0,056719
P10-Magic of the City	47	1.000	0,000249	–	–	–
P16-Web of Public Transport	47	1.000	0,000249	20	1.000	0,009755
P35-Household Mix	47	1.000	0,000249	–	–	–
P48-Housing In Between	47	1.000	0,000249	14	0.700	0,056719
P89-Corner Grocery	47	1.000	0,000249	16	0.800	0,020225
P95-Building Complex	47	1.000	0,000249	–	–	–

The rehabilitation baseline shows multiple patterns with maximum connectivity (DC = 47; normDeg = 1.0), while their counterparts in the peripheral network are frequently absent or show reduced normalized degree. For example, among the ten most connected patterns in the baseline, several are absent from the peripheral network (e.g., P10, P35, P95, P130), while others remain present but with lower integration (e.g., P9: normDeg $1.0 \rightarrow 0.70$; P129: $1.0 \rightarrow 0.50$). This comparison yielded ten anti-pattern (AP) categories, each defined as a recurrent constellation of missing or fragilized baseline-salient patterns rather than as isolated omissions. The full anti-pattern set is not reported here. Instead, we present one worked example randomly selected from the ten APs to illustrate the derivation logic based on network evidence (Table 3).

Table 3. Worked example of anti-pattern derivation from network evidence.

Anti-pattern	Definition (cluster logic)	Absent design patterns (examples)	Network evidence	Practical manifestation
AP10-lack of flexibility	Absence of interconnected adaptability and spatial resilience patterns supporting change over time.	P35-Household Mix P75-The Family P77-House for a Couple P78-House for One Person P127-Intimacy Gradient P196-Corner Doors P205-Structure Follows… P229-Duct Space	High DC/BC in rehabilitated network; null or marginal connectivity in peripheral network.	Rigid layouts unable to respond to household change and variety.

AP10-Lack of Flexibility was derived from the systematic absence (or minimal integration) in the peripheral PMCMV network of architectural-scale patterns that are structurally salient in the rehabilitation baseline. These patterns form a highly connected constellation in the baseline; their absence in the peripheral network suggests the loss of interdependent functions associated with adaptability and spatial resilience. The same procedure was applied to derive the remaining APs [16]: AP01-Urban Disconnection and Isolation, AP02-Monofunctionality; AP03-Disconnection from the Street; AP04-Lack of Communal Areas; AP05-Lack of Resident Protagonism; AP06-Rigid Geometry and Standardization; AP07-Unused Residual Spaces; AP08-Absence of Constructive Refinement; and AP09-Inadequate Environmental Comfort.

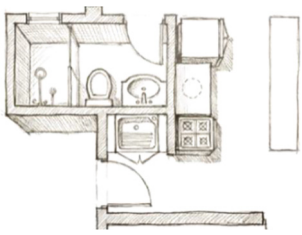
These APs provide the empirical basis for Step 3. Recurrent affordance gaps were mapped from anti-pattern evidence and translated into NPs for rehabilitation-oriented SH design. Initially, 29 candidate solutions were identified from the case study. After overlap removal and comparison with existing patterns [6], the set was refined to 20 NPs. We do not reproduce the full set of NPs. Instead, we outline the three decision layers structuring the NP catalogue (Cities, Architecture and Construction) and present one representative NP: NP19-Technical Core for Progressive Adaptation. NP19 was selected as a worked example because it demonstrates how the proposed method translates an anti-pattern condition into a design-oriented response. It links AP10-Lack of Flexibility and AP08-Absence of Constructive Refinement to a technical-habitable solution that can be applied during rehabilitation design: concentrating service infrastructure to preserve the adaptability of the remaining floor plan (Table 4).

Table 4. Structure of NP19-Technical Core for Progressive Adaptation.

NP19-Technical core for progressive adaptation	
Problem	The dispersion of technical installations constrains future reconfigurations and increases the cost of modifications, often rendering subsequent adaptations financially burdensome or unfeasible.
	The dispersion of technical installations is one of the main constraints on long-term housing adaptability. In existing buildings, fragmented systems across multiple walls and slabs hinder spatial reconfigurations, increasing the complexity of interventions and raising adaptation costs [23]. It usually contributes to functional obsolescence, as any programmatic change requires invasive construction interventions [24, 25].

(*continued*)

Table 4. (*continued*)

NP19-Technical core for progressive adaptation			
Discussion	Concentrating on technical infrastructure zones allows for spaces for reorganization, reducing conflicts between structure, installations, and occupation [26]. Technical cores function as supporting infrastructures. They enable incremental adaptations without requiring extensive demolition [24]. In rehabilitation, this strategy can be relevant. Permanent technical core reconciles the building's constructional limitations, accommodating changes in household composition, domestic practices, or technical requirements in the building's life cycle [23]. Also, it facilitates maintenance and technological upgrades, reducing operational costs and improvised interventions risks [27]. By freeing the rest of the layout for flexible use and future reconfiguration, the technical core supports residential adaptability as a structural quality of the design, extending the dwelling's functional lifespan and reducing the need for invasive interventions over time [23, 27].		
Solution	Concentrate electrical, hydraulic, sanitary, and other complementary systems within a permanent technical core, freeing the remainder of the layout for future reconfigurations. This core functions as a technical anchor, enabling the housing unit to evolve over time without invasive interventions.	Graphic scheme	

4 Conclusions

This study demonstrates how pattern languages can be empirically extended to address SH rehabilitation. By mapping Alexander's pattern CO in rehabilitated buildings and comparing them with peripheral developments, it reveals differences in both pattern presence and structural relationships. Rehabilitated cases showed denser networks, while the peripheral sample displayed weaker relational structures, supporting the identification of recurrent absences and fragmentations interpreted as anti-patterns (APs).

Building on this evidence, the study translated APs conditions into affordance gaps and identified design responses observed in rehabilitation cases that counteracted these deficiencies. Through a process of refinement, these responses were codified into a set of 20 taxonomically structured NPs. The practical relevance of the proposed NPs lies in their capacity to translate recurrent problems of SH – such as fragmented technical systems and limited adaptability – into spatial configurations that can inform early design decisions. In this sense, the contribution to more generative and context-sensitive rehabilitation strategies is linked not only to material reuse, but also to extending building service life through adaptable, maintainable, and socially integrated configurations.

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Methodological Approach of the NEXUS WEF in a University: Sustainable Management in the University Restaurant of UERJ

Diogo Fernandes Rosas(✉), Diego Sebastian Carvalho de Souza, Fábio Santos Carvalho, Elmo Rodrigues da Silva, and Alfredo Akira Ohnuma Jr.

Universidade do Estado do Rio de Janeiro (UERJ/DESMA), Rio de Janeiro, RJ, Brazil
rosas.diogo@posgraduacao.uerj.br

Abstract. The high demand for natural resources and climate change require integrated management approaches capable of balancing the pillars of sustainability. This study aims to apply a methodological approach to the NEXUS Water Energy and Food (WEF) concept, implementing sustainable solutions regarding resource demand on the campus of the State University of Rio de Janeiro, Maracanã, Rio de Janeiro-RJ-Brazil. The methodology included characterizing the facilities and resource use associated with the NEXUS WEF at the University Restaurant, enhancing the analysis of quantitative and qualitative parameters related to consumption volume (water), installed and consumed power (energy), and food products purchased and consumed (food). Alternative sustainability technologies were implemented, with the installation of: a rainwater harvesting system with a storage capacity of 90 m^3 of water and a photovoltaic system (solar carports) in three (3) parking spaces on campus, capable of powering electric vehicles and generating an average of 2,359.91 kWh/month, contributing to a reduction in fossil fuel consumption and CO2 emissions. The systems can meet part of the non-potable water and energy demand of the campus, with environmental, social, and economic benefits, in addition to developing research and studies applied to sustainable management at the university, promoting a space for innovation and reference integrating the 3 elements of the Nexus with the principles of the circular economy and energy transition, establishing a replicable methodology for sustainable public administration.

Keywords: NEXUS Water-Energy-Food · Sustainability · State University of Rio de Janeiro · Resource Management · University Restaurant

1 Introduction

Data from the United Nations (2024) [9] project that the world population may reach approximately 9.9 billion inhabitants by 2054. According to Bleischwitz et al. (2018) [3], this increase accelerates demand for natural resources and consequently tends to generate risks and threats to human beings and ecosystems, in different proportions related to water, energy, and food issues.

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According to Mabhaudhi et al. (2019) [7], water, energy, and food are essential resources that sustain life and the livelihoods of society. In this context, Liu et al. (2018) [6] argue that reducing water scarcity, fossil fuel energy use, and food insecurity are interconnected global challenges, given their interdependence and interrelationship.

The Water, Energy and Food Nexus (WEF Nexus) approach seeks integrated solutions and actions to address the scarcity of these three elements (Kurian, 2015) [5]. These actions can be applied at smaller scales, yet with high potential for visibility and replication of the concept.

The global debate on high resource demand and climate change thus underscores the need to develop an integrated methodological approach addressing water, energy, and food through the WEF Nexus framework in academic settings, given that the use of these resources in institutional environments can yield broad reach in research and technological development as a contribution to the field.

This study presents research conducted at a university campus equipped with three sustainable management systems whose interactions create significant potential for applying the NEXUS approach: a Rainwater Harvesting System (RHS), solar car-ports, and a water footprint analysis of the University Restaurant. The objective is to apply a methodological framework for NEXUS analysis at institutional micro-scale, correlating quantitative and qualitative indicators of water, energy, and food across the three systems implemented on campus, under the principles of the circular economy and energy transition.

Beyond the methodological innovation of analyzing the NEXUS at micro-scale, the study is embedded in strategic axes by evaluating the possible interrelationships between these alternative systems in the university environment, reinforcing the potential of the campus as a space for innovation and a sustainable reference for society.

2 Methodology

The study area for this research is the State University of Rio de Janeiro (UERJ), located in the Maracanã neighborhood, in the city of Rio de Janeiro, RJ – Brazil. The University Restaurant (UR) of UERJ is situated in an outdoor area of the campus.

The methodology consists of: (i) analyzing the rainwater harvesting system; (ii) monitoring the carport photovoltaic system; (iii) investigating the water footprint of meals served in the university restaurant; and (iv) conducting an integrated Nexus analysis.

2.1 Rainwater Harvesting System - RHS

The installed RHS (Fig. 1) consists of 6 underground tanks of 15 m^3 each, with a total rainwater storage and utilization capacity of 90 m^3 or 90,000 l. The availability of rainwater was calculated based on historical local monthly precipitation data, the projected catchment area of the roof, a surface runoff coefficient for roofs, and a filtration efficiency factor that disregards first flush deviation and filtration waste. This volume can meet part of the institution's non-potable water demand.

Monthly water consumption at the University Restaurant was estimated for this scenario to monitor how the system can contribute to this reduction. For water quality,

monthly physicochemical analyses are conducted in compliance with applicable local regulations, including: NBR 15.527 (ABNT, 2019a) [2], NBR 16.783 (ABNT, 2019b) [1] for the use of alternative non-potable water sources, and Ordinance GM/MS N°. 888/2021 (MS, 2021) [8] regarding portability standards, as the most restrictive quality reference.



Fig. 1. Rainwater Harvesting System is installed on campus.

2.2 Solar Carport

The system consists of photovoltaic modules and is composed of 42 photovoltaic panels, with a peak power capacity of 24.75 KWp, capable of powering electric vehicles. With the installation of the solar carport (Fig. 2a and b), monthly energy generation monitoring is carried out to measure the system's potential and capacity to offset conventional energy consumption in the UR.

This monitoring is performed through the S-Miles Enduser application connected to the system, which allows real-time tracking of generation in kW and identification of the system's potential, as well as comparison with the corresponding CO_2 emission reductions. Initially, the system was estimated to generate an average of 2,359.91 kWh/month. However, as the study progresses, it can be observed that the actual value may exceed this forecast.

2.3 Water Footprint of Served Food

The Water Footprint study of food served at the University Restaurant adopts the methodology of the Water Footprint Network, as established by Hoekstra et al. (2011) [4]. This methodology accounts for water appropriation along the entire agricultural and operational supply chain, categorizing consumption into three distinct water components: green, blue, and grey.

The calculation was conducted based on data on the menu offered and the ingredients used in the preparation of the meals served, to obtain the results. The volumes found are



Fig. 2 a. Solar carport installed on campus. b. Electric vehicle charging station.

incorporated into the NEXUS indicator analyses used to develop the interrelationship among the 3 elements.

2.4 Integrated Nexus Analysis

The integrated analysis stage consists of developing the indicators to be identified and evaluated. The effective implementation of this concept depends on the creation and applicability of robust indicators (Table 1), capable of enhancing synergies and efficiencies in the correlations: Water × Energy, Energy × Food, and Food × Water.

Table 1. Example indicators table

Indicators	Unit	Description
Specific water consumption	L/person/day	Average amount of water consumed per person in the building.
Volume of rainwater collected	m^3/month or % of demand	Measures how much of the total demand is met by harvesting systems.
Quality of reused water	Parameters	Compliance indicator against quality parmeters.
Specific energy cosumption	kWh/m^2/month	Energy consumed in the building.
Solar energy generation	kWh/month	Total amount generated by the system.
Avoided CO_2 emissions	tCO_2eq/year	Estimate of avoided carbon emissions.
Water consumption in production	L/Kg	Water volume in UR food production.

Source: Prepared by the author (2026), based on the International Renewable Energy Agency (IRENA). Renewable energy in the water, energy & food nexus.

3 Partial Results and Discussion

The results obtained so far indicate positive trends. Physicochemical parameters (pH, color, turbidity, conductivity, alkalinity, hardness, and chloride) of the rainwater collected by the system were analyzed, and the results were characterized according to the standards established by applicable legislation. These results confirm the suitability of this water for non-potable uses in the study area.

The RHS (90 m^3) can meet part of the campus non-potable water demand in months with adequate rainfall, establishing the first measurable Nexus synergy: each cubic meter of potable water replaced represents energy saved in the utility's treatment and distribution cycle.

The solar carport has been installed, and testing began through app-based monitoring. Figure 3 shows the system's energy production for the period between September 2025 and February 2026. It can be noted that the system produced above the values estimated at the beginning of the project, demonstrating potential that makes it more efficient and enables higher returns for the project. Its peak generation reached 2,551 kWh in December 2025.

To date, the system has recorded a real production of 13.95 MWh, equivalent to a reduction of 14.89 tons of CO_2 emissions, contributing to the minimization of environmental impacts from atmospheric pollutant releases.

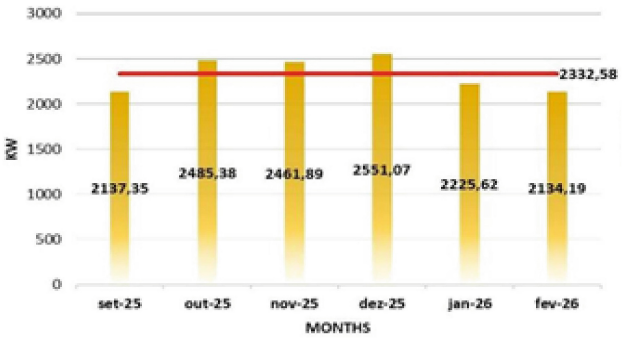


Fig. 3. Monthly energy generation of the solar carport

Regarding the Water Footprint, based on data provided on the food served at the University Restaurant, it was possible to break down its three (3) components by food type. The characterization by food type was subdivided into: protein foods, dairy products, vegetables, legumes, and grains.

Thus, foods such as meat and dairy products have significantly higher WF than plant-based foods. In terms of sustainability, the inclusion of more plant-based foods and fewer animal-origin products can reduce the environmental impact associated with the restaurant's food service. Efficiency in water use can be achieved by replacing high water footprint ingredients with lower-impact alternatives, such as legumes and vegetables, as a strategy for the sustainable management of water resources.

Many challenges are associated with study. Among them, we highlight the collection and integration of sector-specific information, which slows down the implementation process. In this regard, integrated environmental management is necessary to consolidate these data more effectively.

This study is of great relevance as it offers a methodological proposal capable of addressing the identified challenges, applying the NEXUS as an institutional coordination tool with high replication potential in other public institutions. By proposing indicators applicable to this context, the research contributes to the strengthening and monitoring of sustainable actions developed by the university, based on reliable data.

4 Conclusions and Recommendations

The partial results obtained up to the conclusion of this work reinforce the potential of applying the WEF Nexus approach in the academic context as a tool to efficiently promote sustainable campus management. Based on the preliminary analyses con-ducted across the three axes comprising the Nexus, the technical feasibility and potential positive impacts of integrating these systems in the university environment are evident.

As these are preliminary analyses, it should be noted that conclusive changes may still occur based on results.

In the Water axis, the water quality analysis of the rainwater harvesting system demonstrated satisfactory results, within the recommended standards for non-potable uses, in accordance with NBR 15527:2019. These data validate the qualitative water safety and efficiency, indicating that the system can operate adequately. Continued monitoring will improve understanding of the system's capacity in response to seasonal variations and provide data for potential expansion and application to others buildings on campus.

Regarding Energy, the preliminary assessment of the photovoltaic solar generation system through the installed solar carports indicates a positive energy generation outlook, in line with the installed system's potential. The average monthly generation estimate represents an important contribution to the local energy matrix and to the mitigation of CO_2 emissions, while also being integrated with the electric mobility system. Should the research yield satisfactory and concrete results, the system opens pathways for new expansion possibilities and the pursuit of an energy model capable of minimizing total dependence on utility providers.

Regarding Food, the Water Footprint results from the university restaurant revealed important data on the dietary habits of users and the characteristics of meals served. These data enable the development of strategies for reducing institutional water footprint and promoting initiatives involving sustainable food education for the academic community, contributing to more conscious food choices.

In light of the findings, the relevance of the WEF Nexus approach as a fundamental tool for rethinking natural resource management in the institution is emphasized Adopting integrative practices around the WEF Nexus enables improvements in institutional processes and consolidates the university as a space for innovation and commitment to sustainability.

Universities and research centers can play a fundamentally important role in documenting, analyzing, and disseminating case studies, to foster replication of best practices and adapt them to different contexts.

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RERoadS Project: A Methodological Framework to Improve Environmental Awareness of Students and Renovation Process of Italian School Buildings

Marta Maria Sesana[1(✉)], Elisa Di Giuseppe[2], and Andrea Giovanni Mainini[3]

[1] Department of Civil Engineering, Architecture, Land and Environment, and Mathematics, Università degli Studi di Brescia, Brescia 25121, Italy
marta.sesana@unibs.it

[2] Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Ancona 60131, Italy

[3] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan 20133, Italy

Abstract. In Italy, 57% of school buildings are almost 50 years old and are characterized by poor energy performance, high climate impact, and inadequate Indoor Environmental Quality (IEQ). The urgent need to renovate these buildings in order to achieve carbon neutrality and improve indoor air quality has become a priority on the political agenda. Although the urgency of intervention is widely acknowledged, several barriers—related to both financial and cultural constraints—still hinder the large-scale renovation of school buildings. In this context, the RERoadS project aims to address this challenge by proposing a methodological framework based on three interconnected objectives: the implementation of a School Building Renovation Passport in line with current EU directives; the development of dedicated Educational Paths aimed at raising environmental awareness within the school community and tailored to students at different educational levels; and the establishment of a School Advisory Board, a multidisciplinary group of external experts, such as, academics, school managers, local authorities, and policy makers, to provide qualified scientific support for renovation decision-making processes. This paper presents the RERoadS methodology and tools aimed at reshaping the Italian school building sector towards more effective renovation processes and increased sustainability awareness.

Keywords: Sustainability Education · Circularity Awareness · Digitalization · Building Renovation Passport · Educational paths

1 Introduction

The Italian educational building stock comprises a total 30.604 schools, including 15.907 primary schools, 7.737 secondary 1st grade schools, and 6.960 secondary 2nd grade [1]. Most of these buildings were designed and constructed according to regulatory,

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technological, and environmental standards that no longer reflect current requirements. Nearly 57% of the national school building stock is nearly 50 years old [2] and is characterized by poor energy performance and high environmental impact.

Although the urgency of intervention is widely acknowledged, several barriers still hinder the large-scale renovation of school buildings. While some barriers are linked to financial and economic constraints, others are rooted in limited cultural awareness of the importance of such interventions [3]. In this context, fostering awareness and environmental responsibility has become a strategic priority to support the renovation of the existing school building stock towards healthy, energy-efficient, and zero-emission schools. Sustainability education represents a fundamental step that should be introduced from the earliest learning stages [4]. Various initiatives have been developed to educate students on sustainability-related issues through innovative and effective methodologies, such as serious games and game-based learning [5].

The imperative to enhance awareness and accelerate renovation efforts is further reinforced by national and European targets on carbon neutrality, energy efficiency, and indoor air quality [6]. Addressing these challenges requires effective, scalable, and replicable tools and strategies capable of supporting large-scale renovation processes across diverse territorial and climatic contexts.

The European regulatory framework supports these efforts through the Energy Performance of Buildings Directive (EU) 2024/1275 (EPBD IV), which strengthens long-term renovation strategies and introduces new instruments to accelerate deep renovation processes across Member States. Among these, the Building Renovation Passport (BRP), introduced in Article 12, provides a structured and tailored roadmap prepared by qualified professionals to guide staged building renovation processes [7]. Unlike the static Energy Performance Certificate (EPC), the BRP provides a strategic roadmap for progressively achieving higher performance standards, from nZEB to ZEB levels. It must be accessible to both users and digital systems, enabling integration with national and European public data platforms and improving information interoperability [8].

From this perspective, an integrated and coordinated effort among multiple stakeholders in the educational, construction, administrative, technical, and research sectors is essential to develop a tailored instrument specifically designed to address the technical, functional and environmental needs of school buildings. In response to the outlined challenges, the national research project "Renovation and Education Roadmaps for Healthy and Resilient School Buildings towards Carbon Neutrality" (RERoadS), funded by the Italian Ministry of University and Research, aims to support large-scale renovation pathways for school buildings through the development and validation of the first School Building Renovation Passport (SBRP) for the Italian context, focused on sustainability, energy performance and Indoor Environmental Quality (IEQ). The project also promotes dedicated Education Paths (EP) to increase environmental awareness within school communities and encourage sustainable behaviours among younger generations. In addition, it establishes a School Advisory Board (SAB), bringing together researchers, professionals and stakeholders to provide scientific and technical support for school renovation decision-making processes. Besides this introduction, the following

sections foreseen the IMRAD structure: Sect. 2 describes the REROadS methodological framework; Sect. 3 outlines the REROadS outcomes; Sect. 4 focuses on REROadS results; finally, Sect. 5 presents conclusions and further works.

2 REROadS Methodological Framework

The REROadS project seeks to address the identified challenges described in Sect. 1, following a methodological framework (Fig. 1) structured into 4 main phases.

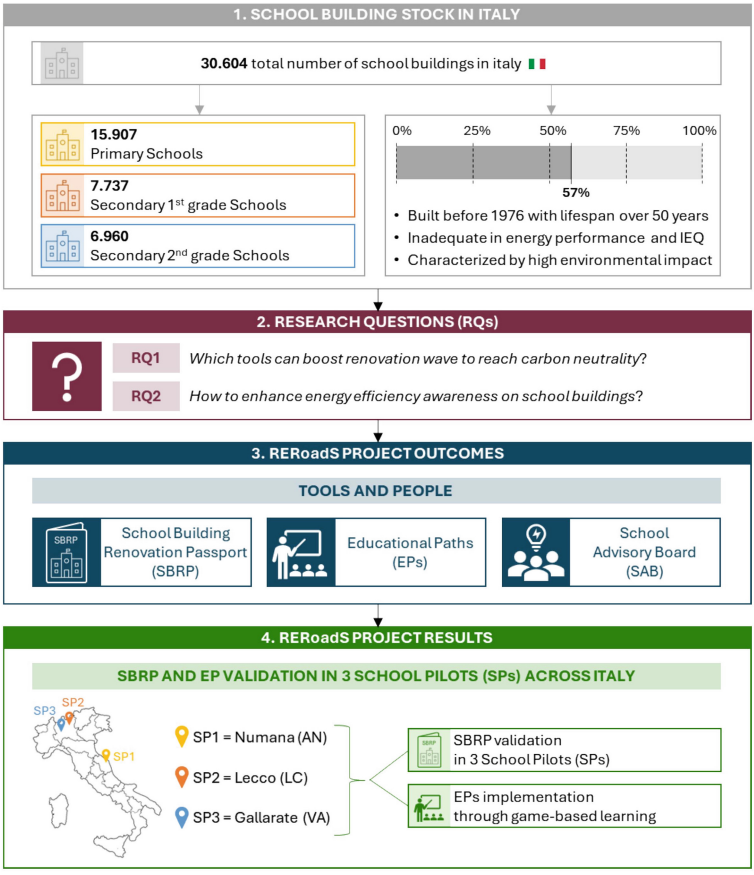


Fig. 1. Graphical overview of the methodological framework adopted by REROadS project. Source: authors' elaboration.

In phase 1, a deep analysis of the school building stock in Italy has been conducted to identify main issues and challenges to be addressed and led to the identification of two main Research Questions (RQs) of phase 2: RQ1) How to enhance energy efficiency awareness on school buildings? RQ2) Which tools can boost renovation wave to reach carbon neutrality?

The phase 3 focuses on the development of the RERoadS project outcomes, derived from the RQs, corresponding to three distinct but interconnected instruments.

(1) The creation of the first SBRP, aimed at facilitating the deep renovation processes required by current EU directives by proposing a tool specifically tailored for school buildings.
(2) The development of dedicated EPs for school communities based on innovative teaching methods, addressing the need to promote sustainability awareness among younger generations.
(3) The creation of the SAB, to support the development of EPs and SBRP, ensuring their coherence, applicability, and effectiveness.

Finally, in phase 4 the project results are validated into three School Pilots (SPs) across Italy.

3 RERoadS Outcomes: Tools and People

The RERoadS outcomes respond to the main project RQs by the creation of two tools (SBRP and EPs) in reply to RQ1 and a group of experts (SAB) to RQ2. In the following subsections the overall process for their development and definition are presented.

3.1 RERoadS School Building Renovation Passport

The RERoadS School Building Renovation Passport represents the first BRP experience tailored for schools in the Italian context, aligned with current EU regulation and targets. The RERoadS SBRP is intended as an efficient and user-friendly tool guiding staged and performance-oriented school renovation processes. Its overall structure is based on the majority of the existing and in use BRPs, including two main elements: the Digital Building Logbook (DBL) and the Renovation Roadmap (RR).

The DBL is a digital tool designed based on an analysis of existing DBL frameworks, including ALDREN, iBRoad, X-Tendo, EUB SuperHub, as well as more recent initiatives such as OneClickReno and GreenReno. These are adapted considering the Italian context and the building typology, as no dedicated DBL frameworks for educational buildings were identified in the literature. The RERoadS DBL is conceived to be closely interconnected with existing Italian educational and building databases, including Unica – Scuola in Chiaro, Portale Unico dei Dati della Scuola, and Anagrafe Regionale Edilizia Scolastica 3.0, including information on energy performance, Indoor Environmental Quality (IEQ), and sustainability. This integration enables a simplified compilation process for the assessor through the automatic pre-filling of indicator values that are easily accessible in the databases. The DBL aims not to function as a static repository but supporting informed decision-making and ensuring data continuity throughout the building lifecycle.

Starting from the DBL data collection, a tailored Renovation Roadmap (RR) is generated according to the school building's current condition and characteristics, identified by selected key performance indicators such as school building archetype, construction technologies, and system configuration. The RR outlines a long-term, step-by-step

renovation pathway proposing a sequence of tailored, cost-effective, and sustainable Elementary Renovation Actions (ERAs), including envelope insulation measures, integration of renewable energy solutions, and replacement of obsolete technical systems, taking into account the preferences or requirements expressed by the school building owner as well as the available incentives in Italy [9]. The roadmap supports a progressive planning approach, moving from low-cost measures to deep retrofit strategies according to the building's characteristics and its assessment in terms of energy performance, IEQ, and sustainability. The RR validation, applied to the three SPs, consists of a detailed analysis comparing the interventions suggested by the roadmap with the results obtained through building performance simulations.

3.2 RERoadS Educational Paths

The development of targeted Educational Paths (EPs) aims to raise environmental awareness within the school community. This activity primarily involves students and teachers, while also indirectly influencing families and the broader school community. The EPs are tailored to students at different educational levels, including primary school, lower secondary school, and upper secondary school. Rather than delivering a purely technical training program, RERoadS adopts innovative educational methodologies to design diverse learning experiences for students of different age groups. These approaches ensure an appropriate level of complexity and engagement, while emphasizing experiential and participatory learning.

For primary school students, introductory modules address basic sustainability concepts in the construction sector, including bioclimatic design, building life cycle, energy efficiency, and carbon footprint, combined with hands-on laboratory activities. Conversely, students at higher educational levels are engaged through quiz-based and game-based learning strategies aimed at enhancing critical thinking and decision-making skills related to energy-saving behaviors and emission reduction.

3.3 RERoadS School Advisory Board

The establishment of the School Advisory Board (SAB) is closely connected to the first two outcomes. The RERoadS SAB is a multidisciplinary group of external experts providing scientifically informed guidance for school renovation decision-making, involving representatives from academia, school management, local authorities, and policy makers. SAB members are actively involved throughout the project development process. The collaboration among these diverse stakeholders contributes to providing expert input and strategic advice that supports the design and refinement of both the SBRP and the EPs.

4 RERoadS Results

The RERoadS results correspond to the validation of the outcomes, tested in three SPs, and in this section the current level of their implementation is presented.

4.1 RERoadS SBRP Application to School Buildings for Validation

The validation of the RERoadS SBRP is planned to be carried out in three SPs located in different geographic contexts and presenting different geometric, technological, and energy characteristics, enabling the generation and testing of differentiated SBRP roadmaps. Specifically, SP1 is a primary school, located in Numana (Marche region – climate zone D); SP2 is a secondary 1st grade schools located in Lecco (Lombardia region – climate zone E); and SP3 is a secondary 2nd grade schools located in Gallarate (Lombardia region – climate zone E). Currently, the SBRP is under construction in a modular structure as described in Sect. 3.1 and it will be used as decision-support tool for defining renovation interventions based on information regarding the current state of the building.

4.2 RERoadS EP Implementation Through Game-Based Learning

The second result of the RERoadS project is the implementation of targeted Educational Paths (EPs). To date, three out of the five educational modules planned for primary school have been implemented in the School Pilot (Fig. 2). The first module, "Discovering Our Green Footprints", introduced students to the environmental impact of human activities and buildings throughout their life cycle. Through practical experiments, including a classroom demonstration of the greenhouse effect, students critically reflected on individual and collective behaviours associated with high ecological footprints. The second module, "Homes Around the World: Building with Climate", focused on the principles of climate-responsive design across different environmental and construction contexts. Working in groups, students developed models of traditional building archetypes representative of different climatic regions worldwide. In the third module, "Building Planet-Friendly Buildings", students explored energy-efficiency strategies for buildings. A real-time experiment demonstrated the effectiveness of thermal insulation, while collaborative activities allowed students to design retrofitted buildings adapted to different climatic conditions, learning how renovation strategies should respond to local climate characteristics.

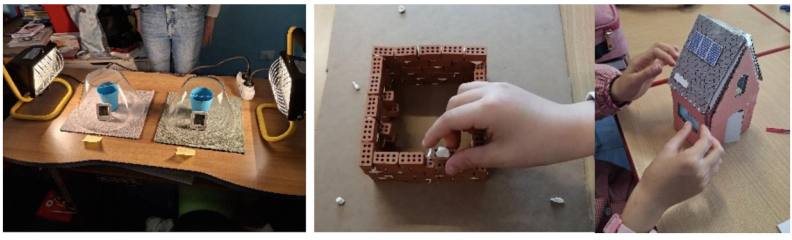


Fig. 2. Images from the three modules implemented in primary school: greenhouse effect experiment, masonry building construction in temperate climate, and planning of energy retrofit interventions for a Nordic climate house.

Regarding secondary 1st grade school, an initial educational activity focused on sustainability and circularity, introducing these topics through interactive team-based

games aimed at calculating students' ecological footprints, quizzes on the principles of the circular economy, and the creation of "Haiku" rhyming compositions related to sustainability themes. A second module aimed to increase students' awareness of their school building, using technical drawings to investigate the building's historical evolution and to introduce the main architectural elements of the façade, while practical demonstrations were also carried out to familiarize students with building survey activities and measurement procedures (Fig. 3).



Fig. 3. Images from the two implemented modules in the lower secondary school where students experienced how to perform an on-site survey of a building both with manual instruments and digital ones.

Besides these experiential learning activities, as a final EP module, RERoadS will develop a dedicated board game addressed to teenage students, aimed at encouraging reflection on the relationship between individual choices, energy consumption, and environmental impact. The RERoadS board game kit will consist of a physical tabletop game designed to allow students to explore how different renovation measures, and the extent of their implementation, can contribute to improving the performance of school buildings and the quality of the surrounding environment.

4.3 RERoadS SAB Technical Meetings

The SAB technical meetings play a key role in supporting the effective implementation of the project outcomes and promoting awareness across broader stakeholder groups. The SAB is composed of representatives from public bodies and local authorities, school building managers and maintenance operators, designers and professionals experienced in educational spaces, direct school users (students, families, teachers, and staff), and stakeholders with expertise in the construction, environmental, educational, and social sectors. SAB's inaugural meeting took place at the end of the first year of the project with the aim of sharing the initial expected results and gathering suggestions for the development of the project's outcomes, in line with the guidelines and needs of all stakeholders in the supply chain.

5 Conclusions

This paper presented the methodological framework, the first results achieved and the next steps planned for RERoadS. The overall project goal is to support school building renovation through an integrated approach combining technical tools, educational initiatives, and stakeholder engagement.

Several activities have already been completed, including collaboration with the three SPs and the involvement of stakeholders within the SAB, whose contributions helped identify operational aspects affecting information exchange and decision-making processes during renovation initiatives. Regarding the EPs, some modules have already been implemented in primary and lower secondary schools, while further activities are planned according to an agreed calendar with teachers of the SPs.

Future developments will focus on the application of the RERoadS SBRP within the three School Pilots to validate the proposed methodology and assess the effectiveness of the renovation roadmaps in terms of energy performance, sustainability, and indoor environmental quality. The pilot applications will contribute to refining the tool and exploring its scalability across the Italian and European school building stock, supporting more effective and sustainable renovation processes.

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How Far Can the Car Go? Assessing the Fifteen-Minute City in Matosinhos

Isabel Paiva[1](✉), Rubén Lois González[2], and Lígia Torres Silva[3]

[1] Civil Engineering Department, School of Engineering, University of Minho, Guimarães, Portugal
pg53558@uminho.pt

[2] Departamento de Xeografía, University of Santiago de Compostela, Santiago de Compostela, Spain

[3] Centre for Territory, Environment and Construction (CTAC) and Lab2PT – Landscape, Heritage and Territory Laboratory/IN2PAST /ICS, School of Engineering, University of Minho, Guimarães, Portugal
lsilva@civil.uminho.pt

Abstract. The Fifteen-Minute City (FMC) model, along with other proximity-centred frameworks, challenges the dominant mobility paradigm that has shaped urban development and contributed significantly to environmental degradation through air and noise pollution and elevated greenhouse gas emissions. This paper aims to: (i) understand the role of public transport (PT) within the FMC; (ii) operationalise the diversity component of the framework developed by Guzman et al. (2024) at a local scale, with a particular focus on PT; and (iii) assess how PT accessibility and perception influence the applicability of the FMC model in Matosinhos. The adopted methodology combines an objective assessment, through spatial analysis, with a subjective evaluation conducted via a questionnaire survey to assess the applicability of the FMC model in the study area. Results show a clear relationship between transport accessibility and functional diversity. Areas with stronger PT provision exhibit higher diversity scores, not necessarily due to greater concentration of local amenities, but due to the extended accessibility enabled by the transport network.

Keywords: Fifteen-minute City · Proximity-based Planning · Urban Resilience

1 Introduction

Cities today face increasing pressure to reconcile urban growth with environmental sustainability, accessibility and quality of life. Over recent decades, many urban areas have expanded through low-density development and dispersed land-use patterns, reinforcing dependence on private vehicles [1]. This has led to higher levels of air and noise pollution and significant greenhouse gas emissions, all of which negatively affect both environmental sustainability and public health [2, 3]. The COVID-19 pandemic further exposed the limitations of mobility-dependent urban systems [4, 5]. Lockdowns re-centred daily

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life around the neighbourhood scale, making disparities in local accessibility more visible and reinforcing the importance of proximity in supporting everyday activities [6]. In this context, proximity-centred accessibility models have gained increasing attention, particularly the Fifteen-Minute City (FMC), which proposes compact, mixed-use neighbourhoods where essential services are accessible within a short walking or cycling distance [2, 4, 6, 7]. The FMC can reduce car dependency, cut down on GHG emissions, and promote active, healthier lifestyles by shifting the focus from long-distance mobility to proximity-based access [8].

While the FMC prioritises walking and cycling within neighbourhoods, it implicitly depends on efficient and accessible PT systems to ensure connectivity between local areas and the broader urban region [6, 9]. As such, proximity and connectivity should not be understood as opposing paradigms but as complementary dimensions of accessibility [2, 10]. Recent conceptual developments of the FMC have increasingly acknowledged this need for integration. Expanding on Moreno's original framework, [9] introduce additional dimensions - such as connectivity, highlighting the importance of linking neighbourhoods through cohesive transport networks. Connectivity ensures that proximity-based environments remain functionally integrated rather than spatially isolated [9], enabling residents to travel easily beyond their neighbourhood when necessary, reducing the need for car ownership while supporting the FMC's proximity goals [6, 11]. Thus, integrating PT within proximity-based planning contributes to broader sustainability goals, making it an enabler within the FMC context [11]. By providing viable alternatives to private car use, it supports modal shifts towards more energy-efficient and equitable forms of mobility [6]. At the same time, PT mitigates one of the key criticisms of the FMC, namely the assumption of self-sufficient neighbourhoods [12, 13], by ensuring that residents are not constrained to limited spatial boundaries and can access a wider range of opportunities without increasing car dependency [4, 9]. Although this study focuses on mobility and accessibility within the framework of the Fifteen-Minute City, it also contributes to the circularity agenda in urban development. By promoting proximity, reducing car dependency, and improving the use of public transport and existing urban infrastructure, the proposed approach supports more efficient use of built assets and helps to limit land consumption, the need for new infrastructure, and resource-intensive urban sprawl. In light of the above, this paper aims to: (i) understand the role of PT within the FMC; (ii) operationalise the diversity component of the framework developed by [9] at a local scale, with a particular focus on PT; and (iii) assess how PT accessibility and perception influence the applicability of the FMC model in Matosinhos.

2 Case Study

The municipality of Matosinhos is located within the Porto Metropolitan Area (AMP) and has a population density of 2.876 inhabitants per km^2, considerably higher than both the metropolitan (864,6 hab./km^2) and national (116,6 hab./km^2) averages [14]. Matosinhos is part of a polycentric metropolitan structure in which the city of Porto functions as the primary urban node, surrounded by several sub-centres such as Senhora da Hora and São Mamede de Infesta [15]. Mobility patterns in Matosinhos reflect

its strong metropolitan integration. Approximately 53% of employed residents work outside the municipality, highlighting the importance of inter-municipal flows in daily mobility. While private vehicles remain the dominant mode of transport (54% of daily trips), active modes such as walking and cycling represent approximately 14% of journeys [14]. These dynamics illustrate both the municipality's accessibility within the metropolitan network and its dependence on motorised mobility. Matosinhos' density, compact urban form and service concentration make it a relevant context for assessing proximity-based accessibility models, with public transport playing a key role in connecting neighbourhoods with different levels of service provision. This paper focuses on UOPG 5, a functional planning unit in Matosinhos based on similar territorial characteristics and urban dynamics [16], selected for its high population density, estimated at approximately 5,539 inhabitants per km^2, and its strategic role as a metropolitan mobility hub, making it suitable for assessing the applicability of the FMC model.

3 Methodology

This study adopts and adapts the analytical framework proposed by [9] for evaluating the applicability of the FMC model at the neighbourhood scale. The FMC Index comprises two main components: diversity and walkability. Diversity refers to the range and balance of essential services available within a fifteen-minute walk from each residential block, while walkability reflects the quality of the pedestrian environment, capturing how safe, comfortable, and feasible it is for residents to walk to those services. Particular emphasis is placed on the operationalisation of the Diversity Index, as it encapsulates not only the physical distribution of services but also the social and behavioural dimensions that condition their relevance to urban life. Thus, two main analyses will take place. Firstly, an objective study that identifies the existing distribution of infrastructure in UOPG 5 (Accessibility). Secondly, an inquiry to the local communities to understand their individual preferences regarding the relative importance of different amenities within walking distance (Individual Preferences). Lastly, the Diversity Index is subsequently computed, taking the previous two analyses into account. By combining these two sources of information, the analysis allows for a more nuanced understanding of accessibility, considering not only the geographical proximity of services but also their perceived relevance to the local population. Given the central role of mobility in shaping accessibility beyond the neighbourhood scale, particular attention is given to the PT category across all analytical dimensions.

Accessibility is operationalised as the number of establishments of a given type that fall within a fifteen-minute walking isochrone drawn from each residential block. In this context, it means measuring the proximity of amenities to each residential building. This analysis is conducted using the Origin-Destination (OD) Cost Matrix Tool from ArcGIS, which enabled the mapping and evaluation of spatial relationships between residential buildings and points of interest (POIs). POIs are classified into six categories of essential services – education, groceries, healthcare, public transport, recreation and services, each composed of many subcategories representing specific types of amenities. Within the PT category, POIs correspond to bus stops, metro stations and railway stations. The accessibility analysis comprises two main steps: i) calculating accessibility per subcategory, where, for each origin and service type, the number of destinations reachable

within 15 min on foot is counted using a cumulative opportunities approach based on the network distance; ii) normalise the accessibility values to allow for comparison between origins and services. To complement the spatial analysis, a questionnaire survey was conducted to capture residents' perceptions of local accessibility and service provision. The survey targeted residents of UOPG 5 and collected information on socio-demographic characteristics, mobility patterns, and the perceived importance of different categories of amenities. Its main purpose was to estimate the relative importance, or weight, of each type of establishment, and, thereby, to understand how residents value and prioritise the selected essential services. In addition, the respondents were asked to indicate which services they considered lacking in their vicinity. This information was essential for identifying residents' priorities and perceptions regarding local accessibility. To compute the resulting weights, which will later be used for the Diversity Index, the weighted linear combination method was used, which integrates the evaluation criteria and their corresponding weights through a weighted average. The Diversity Index captures the equilibrium across different categories of services and incorporates the relative importance that residents assign to each. The diversity score for each block is calculated through a weighted geometric mean of the normalised accessibility values, using the individual preference weights as coefficients.

4 Results

4.1 Accessibility Index

The Accessibility Index reveals a relatively dense but uneven distribution of PT infrastructure within UOPG 5. As illustrated in Fig. 1, which maps the spatial distribution of PT points of interest (POIs), bus stops are widely dispersed across the study area, providing a broad level of baseline coverage. In contrast, metro stations are more spatially concentrated, primarily located along main corridors and central areas, resulting in higher accessibility levels in these zones. This spatial configuration creates differentiated patterns of accessibility. Central areas, where both metro stations and a higher density of bus stops are present, benefit from greater connectivity and redundancy in transport options. Conversely, peripheral and predominantly residential zones rely more heavily on bus services, which, despite their wider distribution, may offer lower service frequency and reduced connectivity. Accessibility values were then normalised using a min–max method.

4.2 Individual Preferences Questionnaire

Using the Weighted Linear Combination method, weights were assigned to each service category. The results indicate that Healthcare (0,22) and Public Transport (0,20) are the most valued categories.

Most respondents report commuting times up to 30 min, which shows that most respondents experience short to moderate commuting times. This does not necessarily align with the 15-min city framework, as the main mode of transportation used is unknown. Nevertheless, considering that nearly half of the respondents commute to

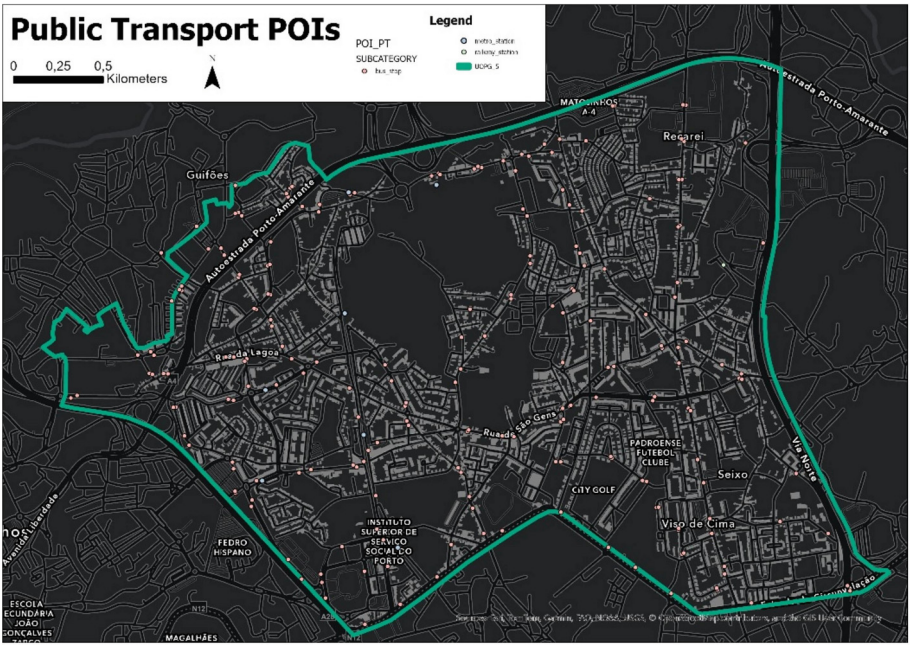


Fig. 1. Public Transport Points of Interest

another municipality, it is reasonable to assume that these journeys are undertaken primarily by PT or private vehicle. Additionally, 18% of respondents travel within the same municipality but to a different parish, and 11% work in the same parish they reside in. Overall, this distribution reinforces the predominance of local and intra-metropolitan mobility patterns, with limited evidence of long-distance commuting among participants.

The mobility patterns help explain why PT emerges as one of the most valued service categories among residents, which may reflect both the current reliance on public transportation for daily mobility or the desire to do so in the future. Interestingly, PT is one of the categories respondents find most lacking. Most respondents chose PT as one of the most deficient categories. Respondents described it as unreliable, complaining about long waiting times and limited destinations. The lack of metro coverage across the municipality was also a popular critic.

4.3 Diversity Index

The Diversity Index, when analysed specifically for the PT category, highlights the role of transport infrastructure in shaping accessibility patterns within UOPG 5. By integrating spatial accessibility with residents' perceived importance, this analysis provides insight into how effectively PT supports proximity-based accessibility. As illustrated in Fig. 2, which presents the spatial distribution of the Diversity Index values for the PT category, higher scores are concentrated in central areas of the study area.

These zones correspond to locations with greater proximity to both metro stations and dense bus networks, resulting in stronger integration within the metropolitan transport

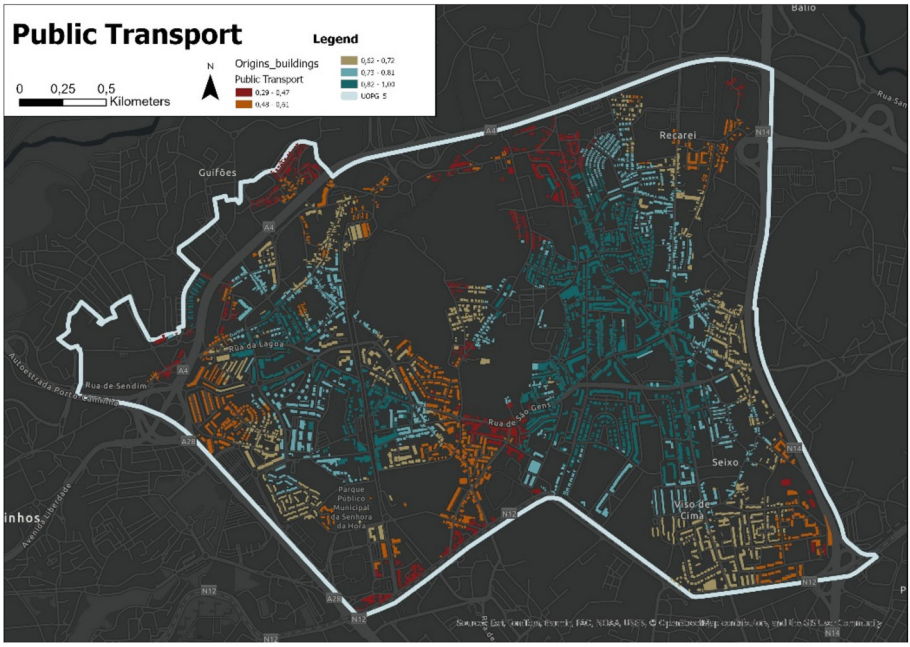


Fig. 2. Diversity Index for the Public Transport category.

system. In these areas, PT enhances accessibility by enabling residents to reach a wider range of services beyond the immediate neighbourhood. In contrast, lower diversity scores are predominantly found in peripheral and residential zones, where accessibility to PT is more limited. These areas tend to rely primarily on bus services, often characterised by lower frequency and reduced connectivity compared to metro corridors. As a result, residents in these locations experience weaker access to the broader urban system, which constrains their ability to compensate for limited local service provision. This spatial pattern reveals a clear relationship between transport accessibility and functional diversity. Areas with stronger PT provision exhibit higher diversity scores, not necessarily because of a greater concentration of local amenities, but due to the extended accessibility enabled by the transport network. Conversely, areas with weaker transport connectivity display lower diversity levels, reinforcing their relative isolation within the metropolitan context.

5 Discussion and Concluding Notes

The results highlight the critical role of PT in shaping accessibility within proximity-based urban models. While the study area presents relatively favourable conditions for spatial accessibility, these are not sufficient to ensure equitable access to services across all neighbourhoods. Mobility emerges as a critical enabling factor. The effectiveness of the FMC in metropolitan contexts depends not only on proximity-centred accessibility but also on broader transport connectivity. Without effective alternatives to private car

use, the principles underpinning the FMC risks remaining aspirational rather than operational, which explains why the category of public transport is comprised both in the accessibility and diversity indexes. Areas with higher Diversity Index scores not only encompass greater concentration of local services but also benefit those with stronger integration within the metropolitan transport network. These findings challenge simplified interpretations of the FMC as a purely localised and self-sufficient urban model. Although proximity-based planning seeks to reduce dependence on long-distance mobility, the questionnaire's results show that daily life within UOPG 5 remains strongly connected to inter-municipal commuting dynamics. PT emerged simultaneously as one of the most valued and most deficient service categories, reflecting the extent to which residents rely on metropolitan mobility networks while also perceiving significant shortcomings in their quality and coverage. In this sense, proximity and connectivity should not be understood as opposing paradigms, but as complementary dimensions of accessibility. Furthermore, the study highlights persistent territorial inequalities within the study area. Peripheral and predominantly residential zones continue to experience weaker accessibility due to lower transport frequency, limited modal diversity and reduced connectivity to metropolitan corridors. This suggests that implementing the FMC may reproduce existing spatial inequalities if proximity-based planning is not accompanied by stronger investment in sustainable mobility systems and inter-municipal coordination. Methodologically, the Diversity Index provides a useful overview of functional accessibility by integrating objective spatial analysis with residents' perceived priorities. Nevertheless, treating all POIs equally may oversimplify the complexity of urban experience, as services differ in scale, frequency of use and social relevance. Future research should therefore further explore the relationship between objective proximity and perceived accessibility, while developing more nuanced weighting systems capable of capturing differentiated urban needs and mobility practices.

Finally, although the study is centred on mobility and accessibility, its findings also contribute to circularity in the construction sector by showing how proximity-based planning and improved public transport connectivity can enhance the use of existing urban infrastructure, reduce car-oriented spatial demands and support more resource-efficient urban development.

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Light Pollution and Climate Change: Evidence from the Last 10 Years and the Need to Integrate Regional Analyses

Laysa Guimarães Vieira Fonseca[1(✉)], Ricardo Nacari Maioli[2], Izabela Uliana Pellegrini[2], Victor Moura Bussolotti[2], and Cristina Engel de Alvarez[2]

[1] Department of Architecture and Urbanism, Federal University of Espírito Santo, Vitória, Brazil
laysagvf@gmail.com

[2] Postgraduate Program in Architecture and Urbanism, Federal University of Espírito Santo, Espírito Santo, Brazil

Abstract. Climate change and light pollution are interconnected environmental challenges with combined effects on energy consumption, human health, and the biodiversity of urban ecosystems. However, a better understanding of the combination between the topics is still needed. The objective of this study was to map and compare scientific production on the relationship between light pollution and climate change, covering the period from 2015 to 2025, in order to provide a comprehensive overview of the evolution of this knowledge. The methodology consisted of bibliometric research, using PubMed, Scopus, SciELO, and CAPES Journal Portal databases. Although there was an upward trend during the time frame under review, an analysis of the articles revealed fluctuations in scientific output over the period analyzed, with a concentration of publications in recent years, particularly after 2020. The literature reviewed confirms light pollution as a factor reinforcing climate change, manifested by increased energy use and impacts on urban ecology. In conclusion, although the topic is globally rising, the concentration in a few sources and the marked regional gap signal the urgency of integrating this theme into public policies.

Keywords: Artificial Light at Night · Global Warming · Urban Ecology · Bibliometrics · Research Gap

1 Introduction

In the current field of study of urban spaces, light pollution is emerging as a significant factor exacerbating the impacts of climate change. With the invention of electricity during the Industrial Revolution in the 19th century, the large-scale use of artificial lighting in public and private areas began [1]. Consequently, the excess of artificial light, especially in large metropolises, increases electricity consumption, intensifies local warming [2], and contributes to greenhouse gas emissions [3]. Furthermore, rapidly urbanizing

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regions, the expansion of artificial lighting has become increasingly associated with unsustainable patterns of energy consumption and environmental degradation [4]. In the long term, these effects have direct and indirect repercussions on human health and local biodiversity [5, 6]. In this context, Falchi et al. [7] defines light pollution as the alteration of natural nocturnal light levels caused by anthropogenic sources, namely, the excessive emission of artificial light from building facades, billboards, and street lighting that scatters into the atmosphere.

Beyond high energy consumption, light pollution causes significant environmental imbalances. The intensive use of electrical energy for lighting accounts for a considerable amount of carbon emissions, intensifying the effects of climate change. Furthermore, scientific evidence demonstrates that light pollution contributes to environmental degradation in various ways [8]. One of the most perceptible problems caused by excessive artificial lighting in cities is the obscuration of the night sky, which compromises astronomical observation and the human connection with the starry sky [9]. It is estimated that approximately 80% of the world's population lives under skies altered by this glow, leaving few areas where the sky maintains its natural characteristics. It should be noted that 99% of the population in Europe and the United States lives under altered skies, making it almost impossible to see the stars with the naked eye [10]. This loss of stellar visibility represents not only an environmental impact but also a symbolic rupture in the relationship between humans and nature.

In principle, light pollution can harm fauna and flora by altering essential ecological cycles. In fauna, excess artificial light interferes with the behavior of various species, affecting processes such as migration, feeding, and reproduction. In some cases, it prevents mating and the perpetuation of species, as observed in turtles, fireflies, bats, and fish. Regarding flora, excessive artificial light compromises the process of photosynthesis, hindering the conversion of carbon dioxide into oxygen [2]. Additionally, it influences leaf fall and extends the growth period of plants, generating significant effects on local vegetation [11].

The excess of artificial light, besides affecting other life forms, also represents a significant threat to human health, disrupting essential biological rhythms and contributing to a range of medical conditions. Studies indicate that excessive exposure to artificial light can cause eye irritation and chronic fatigue [8]. Additionally, it directly interferes with the circadian cycle, impairing sleep quality and favoring the development of metabolic problems such as obesity and type 2 diabetes mellitus [12, 13]. This circadian dysfunction also leads to the interruption of melatonin production, affecting the synthesis of growth hormone [14, 15], and aggravating psychological disorders such as depression [16]. In the oncological context, there is evidence of an approximately 11% to 14% increase in the risk of breast cancer in women exposed to higher levels of outdoor artificial light at night, even after adjusting for environmental variables such as air pollutants and vegetation index [17, 18].

Despite these evident risks, light pollution remains a largely unrecognized challenge. A lack of public awareness regarding its effects sustains behaviors that worsen the problem [19], such as common sources including residential lamps, unshielded public streetlights, vehicle headlights, and the excessive lighting of urban centers, which reflects off clouds and amplifies the night sky glow [11]. This lack of knowledge negatively

affects personal motivation to adopt correct behaviors [19] and the perception of the issue, compromising its recognition as a legitimate form of ecological deterioration and hindering the development of public policies [8].

Moreover, global entities responsible for formulating government policies have not included light pollution among their priority goals for controlling environmental degradation. It was only in 2020 that the European Union recognized it as an environmental problem [20]. In Brazil, there is a scarcity of debate regarding the excess of artificial light, reflecting negatively in the absence of legislation and standards for the national lighting system. However, the Brazilian Association of Technical Standards (ABNT) has published a new guideline, occupying nearly an entire chapter of a technical standard, which delves further into light pollution, although it remains insufficient [21]. These recent advances highlight the need to integrate light pollution into discussions on climate change and urban ecosystems, urging collective actions to mitigate its impacts.

In this context, this work conducts a bibliographic review of academic production on light pollution from 2015 to 2025. The objective is to synthesize current knowledge on the subject regarding its relationship with climate change, considering its impacts on energy consumption, the environment, and human health.

2 Methodology

This study is characterized as an integrative literature review combined with a bibliometric analysis of scientific production, adopting a qualitative-quantitative approach. The methodological flow was structured into the following stages:

Database Selection and Search Strategy: The bibliographic survey was carried out across national and international databases such as SciELO, PubMed, Scopus, and the CAPES Journals Portal. A "general" search was performed using the "any field" (all fields) parameter. The search was conducted using seven combinations of keywords in Portuguese and English, as detailed in Table 1.

Table 1. Search Terms used in the databases.

Number	Terms
1	"Poluição Luminosa"
2	"Light Pollution"
3	"Artificial Light at Night"
4	"Light Pollution" and "Climate Change"
5	"Light Pollution" and "Climatic Changes"
6	"Artificial Light at Night" and "Climate Change"
7	"Artificial Light at Night" and "Climatic Changes"

Timeframe and Data Organization: The study focused on scientific production from the last decade (2015 to 2025). For analysis and organization purposes, the material was segmented into two five-year periods: 2015–2020 and 2021–2025.

Exclusion Criteria: Editorials, event abstracts, and opinion pieces without evidence were excluded, as well as works without a direct and in-depth correlation between light pollution and environmental or climatic impacts.

Snowballing Technique: For the theoretical framework, the snowballing technique was applied following the guidelines of Wohlin [22]. This consisted of backward snowballing, examining reference lists of key articles to identify primary sources and seminal studies.

Data Systematic Processing: Files were organized into specific folders and a structured spreadsheet, segmented according to the search terms and the defined periods. Duplicate identification and removal were performed using Mendeley software. For each publication, information such as year of publication, country of origin, and primary theme was recorded. During the analysis, it was observed that the results obtained from the isolated search terms presented in lines 1, 2, and 3 of Table 1 were disconnected from the central objective of the research. Therefore, only studies containing combined search terms, as presented in lines 4, 5, 6, and 7 of Table 1, were retained to ensure alignment with the relationship between light pollution and climate change. To identify the geographical origin when it was not explicitly stated, priority was given to the institutional affiliation of the first author, followed by the location of the case study and the journal's editorial affiliation.

Final Sample Refinement: A detailed review was conducted by reading the abstracts of the identified studies to exclude "false positives" such as studies mentioning light pollution without addressing its relationship with climate change. This stage also included a final check for duplicates, ensuring the quality and precision of the analytical set.

3 Results

The study selection process revealed a progressive refinement of the sample. Initially, 8,055 publications were identified across the consulted databases, excluding results from Google Scholar. After the first stage of duplicate removal, the number of records was reduced to 4,803.

Upon applying the keyword combination criteria and the established timeframe, the initial volume of studies was significantly reduced to 216 publications. After a meticulous screening, a preliminary corpus of 99 documents considered potentially relevant to the research was defined. This relatively small number reflects both the specificity of the scope and the relative novelty of the theme in the current academic landscape.

During the bibliographic survey, a near-absence of publications in Portuguese addressing the direct intersection between the two central themes of this research was observed. This disparity may be attributed, in part, to the specificity of the descriptors used; while the searches in English integrated combined terms (as per lines 4 to 7 of Table 1), which effectively filtered the correlation between artificial light and climate, the results in the Portuguese language (primarily obtained through the single descriptor "Poluição Luminosa") tended to focus on fragmented aspects of the phenomenon, lacking the climatic connection required by the inclusion criteria. This highlights a gap in integrated scientific production within Portuguese-speaking countries, reinforcing the need for research that unifies these axes.

After the systematic refinement process described in the methodology, the final analytical set consisted of 90 studies. The quantitative and qualitative analyses of these publications are presented below, beginning with the temporal and geographical distribution of the production.

The analysis of the temporal distribution of the publications revealed variations throughout the observed period. The year with the highest number of published studies was 2021, with 17 publications. This was followed by 2024, with 11 publications, and 2017, with 10 studies. Figure 1 shows the total amount of publications by year.

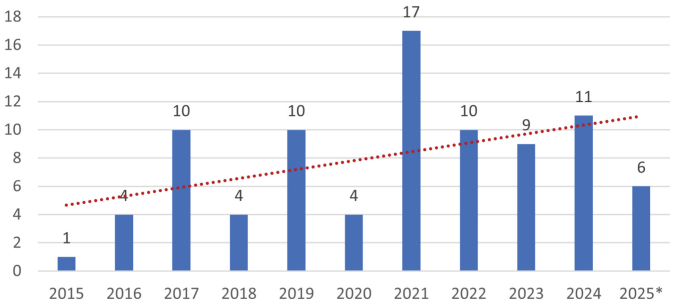


Fig. 1. Number of publications by year with a trend line for the period analyzed.

It can be observed that the growth in the number of publications was not constant and that there is no clear line of trends. Although the number of publications varied throughout the analyzed period, greater concentration of studies can be observed in recent years, showing an upward trend. Also, the year 2025 presented 6 publications, a figure lower than those observed in previous years. This result may be attributed to the fact that data collection was conducted during 2025, which may have limited the identification of studies that had not yet been published or indexed in the consulted databases at the time of the research.

The study of the geographical origin of the publications also revealed a significant concentration of research in Northern Hemisphere countries. Figure 2 presents the percentage of publications by continents. It can be noted that almost half of the production comes from Europe and almost 3/4 comes from its combination with North America. Less than 15% of the studies come from the Global South.

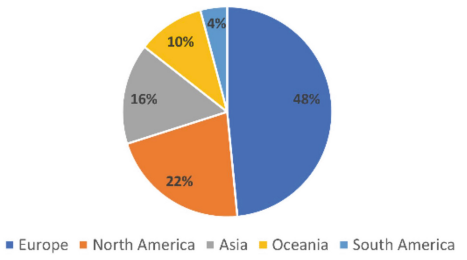


Fig. 2. Percentage of publications by continent.

These data indicate a predominance of research developed in Europe and North America, while scientific production in other regions of the world remains more limited. Among the countries with the highest number of publications, the United States stood out with 16 studies, followed by the United Kingdom with 11, and Germany with 9 publications. Figure 3 consists of a map with the numerical distribution of the publications by countries.

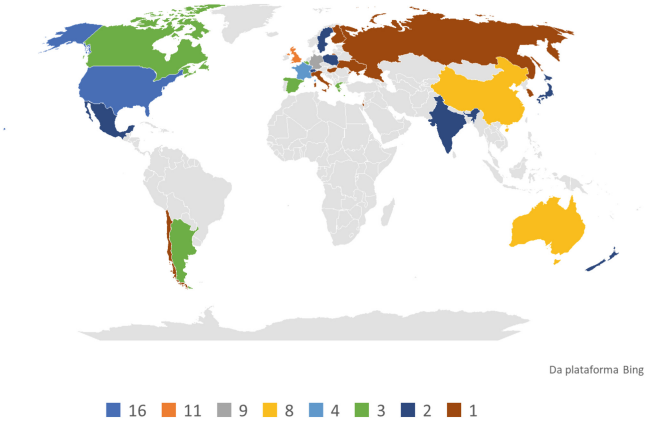


Fig. 3. Number of publications by country.

In South America, only Argentina, with 3 publications, and Chile, with 1, had identified studies in the area. In Oceania, Australia concentrated 80% of the publications. In Asia, China had around half of the publications of the continent.

4 Conclusion

The predominance of studies published in Europe and North America may be related to factors such as greater investment in scientific research, higher availability of technological infrastructure, and a more robust inclusion of environmental themes in the scientific and political agendas of these regions. Furthermore, European and North American countries possess a consolidated tradition in fields such as astronomy, remote sensing, and urban ecology, disciplines that frequently address light pollution as an object of investigation.

Advancements in satellite monitoring technologies and the growing scientific interest in the environmental impacts of urbanization have also contributed to the expansion of research on this topic [4]. On the other side, the low volume of publications in South America, particularly in Brazil, reveals a significant gap in regional scientific production. Although light pollution is present in major Latin American urban centers, the subject still receives limited attention within the region's academic circles [23].

This gap may be associated with the limited presence of the theme in environmental research agendas and the absence of specific public policies aimed at monitoring

and controlling this type of pollution. In this context, expanding regional scientific production on the subject becomes desirable to support the formulation of public policies, guide sustainable urban planning strategies, and contribute to actions mitigating the environmental impacts related to the excess of artificial lighting.

Beyond its environmental impacts, light pollution should also be understood as an indicator of inefficient urban resource management. Excessive artificial lighting reflects patterns of energy waste that contradict current principles of sustainable and circular cities. In this sense, addressing light pollution is not limited to protecting biodiversity or improving human health, but also involves rethinking urban lighting systems from the perspective of energy efficiency, environmental balance, and long-term urban resilience. Expanding research on this topic, especially in countries of the Global South, is essential for supporting more sustainable urban development models and environmentally responsible public policies.

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Light Pollution Trends in Santa Teresa, Brazil: A Remote Sensing Study

Kamilly Monteiro Echer[1](✉), Ludmila Brunow Orlandi[2], Ricardo Nacari Maioli[1,2], and Cristina Engel de Alvarez[2]

[1] Departamento de Arquitetura e Urbanismo, FAESA Centro Universitário, Vitória, Brazil
kamillyme@gmail.com

[2] Programa de Pós-Graduação em Arquitetura e Urbanismo, Universidade Federal do Espírito Santo, Vitória, Brazil

Abstract. Light pollution is a global problem caused by the inadequate use of artificial light in the nighttime. The excess of artificial light causes changes not only in human life, but also in fauna and flora. The impacts are not only visual, and its inappropriate use is causing negative effects in several cities in Brazil and around the world, especially in regions undergoing territorial expansion. Thus, this research aims to analyze the evolution and trends of light pollution in the city of Santa Teresa, Brazil, through remote sensing from 2012 to 2024. The choice of this city is justified by the fact that it is a regional landmark due to its large areas of preserved Atlantic Forest, where high biodiversity stands in stark contrast to the city's rapid urban and population expansion driven by tourism over the past decade. The methodology is based on the analyses of annual light pollution maps generated from Visible Infrared Imaging Radiometer Suite (VIIRS) satellite imagery. With this method of analysis, it was possible to observe that there was an expansion of the urban territory with radiance emission, which can have a negative impact on local biodiversity, especially in regions further away from the urban center of the city. This study highlights the importance of proper planning for the expansion of cities and can assist in the implementation of mitigation policies for this type of problem. This will strengthen the dialogue between science and society in a city undergoing rapid expansion.

Keywords: Artificial Light at Night · Urban Expansion · Light Pollution Map · Radiance · VIIRS

1 Introduction

Light pollution is described as the inappropriate use of Artificial Light at Night (ALAN), whose oversizing causes drastic changes in the life of every living being [1, 2]. The daily, lunar, and seasonal cycles of natural light have been fundamental forms of environmental variation on the Earth's surface since the emergence of life [1], and the common use of natural light has been affected by the introduction of artificial light over the last few centuries as territorial expansion has occurred around the world, with the misuse of

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public and domestic lighting. This has disrupted the human circadian cycle, fauna, and flora, and even the observation of celestial bodies, although there are new technologies that establish better use of ALAN [2, 3].

In recent decades, there has been rapid development of urban and industrial areas, largely at the expense of natural areas and open spaces [4]. The territorial expansion driven by rapid urbanization has intensified the excessive and inappropriate use of artificial light, a consequence that is reaching even regions far from large urban centers in Brazil. As a result, artificial light expands beyond city limits, reaching environmental preservation areas, posing risks to native vegetation and causing imbalances in environmental and climatic conditions throughout the biological process [5]. The inappropriate use of artificial lighting disrupts the nightlife of the entire local ecosystem and can impact a large number of species in environmental preservation areas, such as those in the municipality of Santa Teresa, Brazil, famous for its hummingbirds.

The exponential evolution of this region is directly linked to growing economic investment in the tourism sector, seen as one of the main sources of income in the region [6]. This factor has intensified the demand for urban landscape adaptation in terms of aesthetics and safety, directly influencing the expansion of the urban perimeter to supply local infrastructure. This has led to a significant increase in nighttime lighting, even in regions that are not yet urbanized.

Given this scenario, there is a growing need to raise awareness among the population and managers of these communities to harmonize the adoption of sustainable practices in the use of lighting as a result of expansion in risk areas, especially in regions of recent growth. As discussed by Freitas *et al.* [7] and Kyba *et al.* [8], studies on the spatial patterns of artificial nighttime lighting have been conducted predominantly in China, Europe, and North America, with little consideration given to tropical regions. The lack of more comprehensive terrestrial observations makes it difficult to construct global maps that establish sources of information and control the inappropriate expansion of ALAN, although smaller scales can and should be analyzed in greater detail [7].

As a way to encourage research on the topic in the region, this article aims to analyze the evolution of light pollution from 2012 to 2024 based on territorial expansion in the municipality of Santa Teresa, Brazil, through remote-sensing images of nighttime lights. Brazil, home to one of the world's greatest biodiversities, is a valuable field of study on the consequences of light pollution in conservation areas, and Santa Teresa, which encompasses a vast territory of the Atlantic Forest, is an important case study.

2 Methodology

The methodology is based on a territorial analysis of Santa Teresa, referring to the advance of light pollution through annual nighttime light maps produced from satellite images between 2012 and 2024. For the arrangement of the procedures adopted, this chapter was structured in three stages: I) presentation of the research area; II) data collection on territorial expansion; III) investigation of the light pollution database.

2.1 Presentation of the Research Area

Santa Teresa, a mountainous municipality in the state of Espírito Santo (Fig. 1), covers an area of 683.032 km^2 [9]. In the last population census in 2022, there were 22,808 inhabitants residing in the territory. The city is known for its mild climate, extensive Atlantic Forest preservation area, and cultural and gastronomic traditions, which drive the economy through tourism.

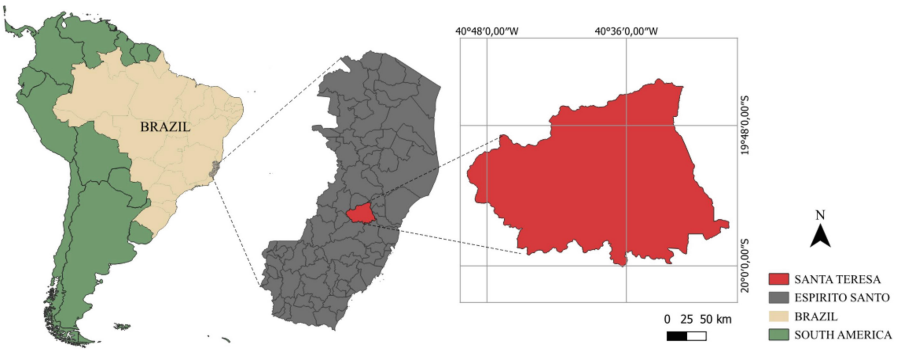


Fig. 1. Location map of the city of Santa Teresa, Espírito Santo.

2.2 Data Collection on Territorial Expansion

A review of historical census data compiled by Google Earth and IBGE - Instituto Brasileiro de Geografia e Estatística - showed that the territorial expansion of Santa Teresa is not directly linked to population growth. From 1980 to 2022, there was a decline in the region's population [9], and since it is a region driven by agrotourism, it is clear that the city's expansion is related to the growth of tourist activities. The municipality needed greater investment in landscape enhancement, leading to improved urban infrastructure in order to provide better mobility and experience for visitors [10]. Thus, occupation in preservation areas became a common practice to improve the region's source of income.

According to the comparative analysis of a historical series of aerial images generated from the research site, there was a change in land use from 2012 to 2024 (Fig. 2). It can be observed that there was an expansion of areas occupied by humans, mainly in areas close to native forest regions, which are environmental preservation sites.

Regarding temporal evolution through aerial image analysis, it was possible to delimit a region that was most influenced by territorial expansion, for subsequent analysis of the evolution of its light pollution. The selected region contains a considerable percentage of preserved areas, known as the Caravaggio Circuit.

2.3 Investigation of Light Pollution Sources

Due to increased spatial resolution, low light sensitivity, in-orbit calibration, and greater data dynamics, the VIIRS (Visible Infrared Imaging Radiometer Suite) product offers

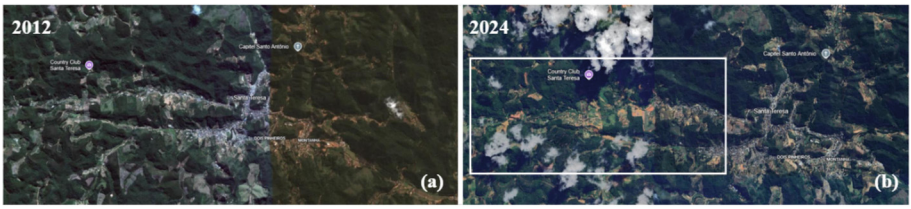


Fig. 2. Historical images of the city of Santa Teresa, Espírito Santo. Evolution from 2012 (a) to 2024 (b). Google Earth, 2025.

significant improvements for the study of socioeconomic phenomena [3]. Therefore, the analysis was carried out by collecting information from the Light Pollution Map portal (www.lightpollutionmap.info), using VIIRS overlay, on nighttime light data available for the period from 2012 to 2024. In this way, an area of the municipality was delimited for an analysis of the general data for the region, in addition to a more approximate cutout referring to the Caravaggio Circuit, in order to obtain a more accurate assessment of this area.

Georeferenced images were generated for each year analyzed. The format used was GeoTIFF with 32-bit floating point pixels, which is a geospatial data storage format related to radiance [11]. After the images were extracted, they were imported and processed using QGIS (Quantum Geographic Information System) version 3.44.4, a free program that allows the visualization, editing, and analysis of geospatial data.

Using the "raster pixels to polygons" tool, each pixel in the imported raster image was converted into an individual polygon within a vector layer. Since each layer represents a specific year, each resulting polygon represents a radiance value that is classified using graduated symbology. Finally, a color gradient was created and used in the map legend in order to preserve the highest sensitivity of corresponding radiance on the map, separated into ten levels of radiance, so that each interval is double that of the previous class (0–0.5–1.0–2.0–4.0–8.0–16.0–32.0–64.0–128.0 $nWcm^{-2}$ sr^{-1}). This grading scale was created and proposed by this study to facilitate visual analysis of radiance levels in the investigated territory.

3 Results

The research was based on the analysis of maps and spreadsheets generated by QGis software for the period from 2012 to 2024, in addition to the IBGE [9]. Although the population data referred to 2010 and 2022, also a 12-year interval, it was understood that the estimate for population growth was minimal and did not interfere with the conclusion of the research.

The analysis of the region challenges the hypothesis of light pollution growth directly linked to population growth. Thus, in this first stage, an increase in population was identified between 2012 and 2024, but there was a 5% drop in *per capita* radiance (Fig. 3a). In 2024, the average radiance value per 1.000 inhabitants decreased to 44.77 $nWcm^{-2}$ sr^{-1}, close to the mean of 45.2 $nWcm^{-2}$ sr^{-1} recorded in Brazil in 2024 [11]. The municipality recorded a mean radiance level of 0.29 $nWcm^{-2}$ sr^{-1} in the analyzes period, due

to its vast unoccupied area, while the national mean was 0.24 nWcm^{-2} sr^{-1}. Therefore, the research focused on territorial expansion as an aggravating factor of light pollution, as a result of the advance into environmental preservation areas.

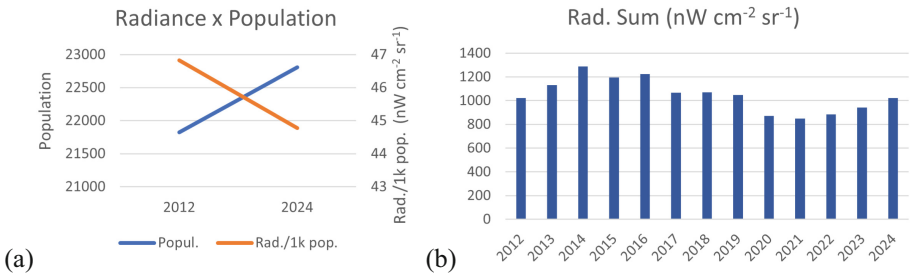


Fig. 3. Population growth and a decrease in *per capita* radiance over a 12-year period (a). Changes in the municipality's total radiance during the period analyzed (b).

In the second stage of the research, the growing territorial expansion of the municipality linked to the advancement of infrastructure that serves the tourism economy was taken into account. The diagnosis based on radiance data and QGIS image processing showed a relative reduction in radiance levels from 2017 to 2021 (Fig. 3b), mainly associated with the adoption of measures to renovate the street lighting system in the city center and its district with LED luminaires [12], which have greater control over their luminous flux. Although the municipality is taking care to produce more sustainable policies, there has been a growing increase in light pollution in recent years. The advance of radiance has become inevitable as the region has expanded.

In the third stage of the investigation, it was possible to verify that a specific region known as Circuito Caravaggio suffered the greatest impact from this recent expansion of the municipality, highlighted in Fig. 4. This is a location renowned for its scenic beauty, characterized by the valleys surrounding Santa Teresa, which in recent years has undergone major urban infrastructure expansion in terms of road systems, hotels and inns, restaurants, among others [13].

According to Kocifaj [14], light pollution produces visible light domes in the night sky near cities, illuminating large areas of the sky and reaching environments that would otherwise be dark, such as protected natural spaces. This phenomenon is noticeable in the region, directly impacting areas further away from the urban center of the municipality, such as the Caravaggio Circuit, a growing region, and reaching environmental preservation areas.

In addition, as it is considered a rural area, the radiance levels become a concern, since an increase in light pollution can be noticed in the region, even without the presence of street lighting. This is worrying because the growth in light pollution is due to the lighting that already exists in the establishments located there. It is common to see lights installed outside buildings to illuminate the area at night. In addition, there are requests for the installation of public lighting in the region due to the growth of road infrastructure, which may lead to more radiance emissions into space. In summary, this

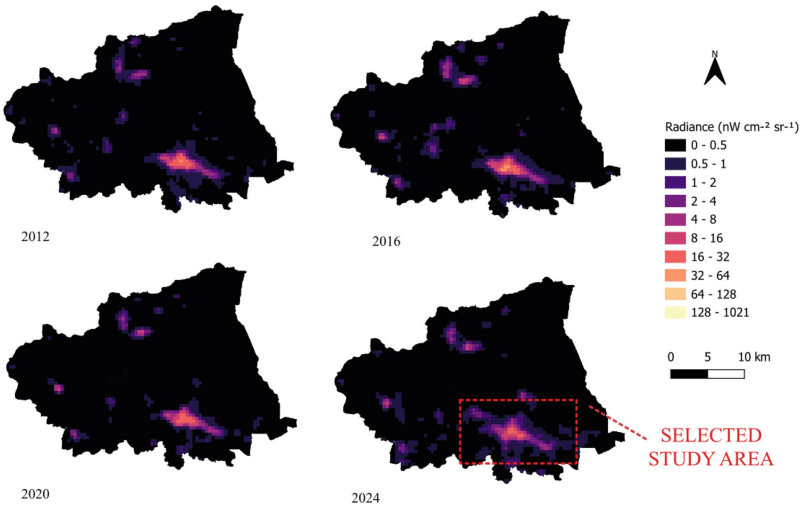


Fig. 4. Changes in radiance levels in the municipality between 2012 and 2024.

fact, combined with an increase in accommodation and leisure establishments in the region, may further aggravate the situation. Thus, when comparing the first year of the analysis (Fig. 5a) with the last (Fig. 5b), it is evident that the occurrence of pixels with radiance is spreading more in the region, reaching a larger portion of the territory and impacting environmental preservation areas adjacent to areas of human occupation.

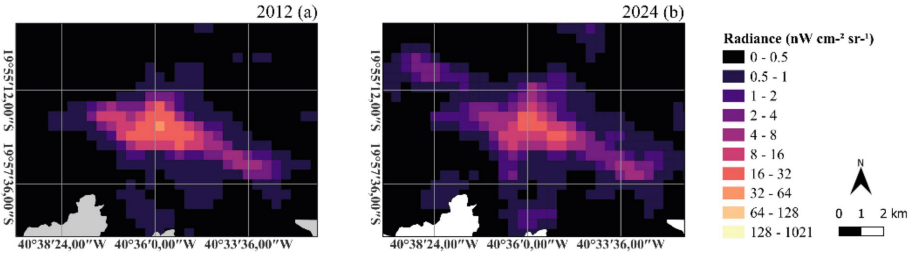


Fig. 5. Analysis of the urban center and the Caravaggio Circuit in 2012 (a) and 2024 (b).

The analysis showed that replacing light fixtures with more efficient models reduced the spread of ALAN in the city, proving to be an effective tool in controlling light pollution by reducing radiance levels. However, it is necessary to constantly inspect and maintain the light fixtures so that the problem does not spread and worsen, as happened in other districts. As the region is surrounded by biological reserves, light pollution can have a negative impact on entire ecosystems. Therefore, the analysis and monitoring of light pollution in this municipality is relevant as an example of environmental protection. Thus, with proper planning, the region has sufficient potential for the planning of responsible and efficient public lighting.

In comparison to this research, we can examine the study conducted on the city of Hong Kong [3]. Despite being a compact city, its high level of urban density classifies it as a region that requires constant investment in major infrastructure works. However, its radiance level remained partially stable during the analysis period, as it is a city that is already consolidated in terms of urban space and public lighting. In the case of Santa Teresa, it is still in the process of expansion and, although its radiance levels are moderate, unlike the Asian metropolis, the average radiance data has shown constant evolution over the last 4 years, and without proper planning, it may become a negative example in this regard. Therefore, it is recommended that preventive methods be implemented to mitigate light pollution in protected areas, integrated into the management plans for these areas, with a focus on local impact and national legislation or guidelines to control light pollution on a large scale [15, 16].

4 Conclusions

The analysis of the advance of light pollution in the municipality of Santa Teresa in line with its territorial expansion shows that greater knowledge about its causes and impacts is needed so that municipal management can plan urban expansion with greater care, reducing the possible impacts caused by artificial lighting. Not only urban planners, but also the population and local entrepreneurs need to be aware of this problem so that they can assist in policing municipal actions and help preserve the ecosystems present in the region, remembering that it is this ecosystem that sustains the economic base of tourism in the city. The mean and per capita radiance values recorded in the municipality are close to the values recorded in Brazil in 2024 [11], which may make this study an example with characteristics similar to those of the country.

Although the levels are not considered an alarming concern, there has been a gradual increase in light pollution in recent years, posing a potential risk that preserved areas will suffer negative influences from night lighting for the sake of tourism. Therefore, as long as urban expansion is properly planned and the population is made aware of the problem, environmental preservation can be guaranteed in the long term, even with the region's territorial expansion.

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The Quality of Life and Urban Participation: Inputs from Kragujevac, Serbia

Branislav Antonić[1](✉), Ivan Radulović[2], and Jovana Stefanović[1]

[1] Faculty of Architecture, University of Belgrade, Belgrade, Serbia
antonic83@gmail.com
[2] City of Kragujevac—Chief Planner, Kragujevac, Serbia

Abstract. The Quality of Life Initiative (QoLI) is a novel programme launched by the UN Habitat in 2023. It is framed to support cities to assess and improve the quality of life at local level, for their inhabitants. Just about 20 cities worldwide have completed the QoLI process. One of these "pilots" is Kragujevac, the fourth city of Serbia. The essence of this process is to guide local policymakers, urban planners, and community leaders through practical steps to form, adjust and adopt the Quality of Life index, based on measuring global- and local-layer indicators. Global-layer indicators are created by the UN Habitat for all participating cities and organised in nine domains. In addition to them, each city had to create at least 12 local-layer indicators through local participation. Furthermore, both types of indicators had to be measured by using different data: statistical data, GIS calculations, mobile ping data and e-survey. The aim of this research is to show the whole QoLI process in the city through the different means of urban participation: information and communication tools, stakeholder meetings, co-creation mechanisms, and comprehensive e-survey with citizens. Such an approach enables forming the final Quality of Life index for the city, which is critical to compare Kragujevac with the other pilot cities in the QoLI, as well as to customise local policy documents and city budget to issues with the most noticeable gaps in the current and desired quality of life.

Keywords: Quality of life · Urban environment · Indicators · Urban development · Global-local

1 Introduction – Quality of Urban Life

In recent decades, urban areas have been increasingly affected by environmental degradation, traffic congestion, spatial overcrowding, and widening socio-economic inequalities, all of which directly influence everyday living conditions [1]. As urbanisation accelerates, the question of how people live, work, and thrive in cities becomes more urgent. These ongoing changes have revealed the need to assess the urban context using a systemic–holistic approach, taking into account both objective and subjective factors [2]. Consequently, within the framework of sustainable urban planning and development, quality of life has emerged as a central evaluative category for measuring socio-economic

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advancement [3]. Its establishment is perceived as one of the main goals of planning policies worldwide [4, 5]. Therefore, global organisations have also attempted to address quality of life in their programmes, albeit without a global consensus on methodology and criteria for selecting the key domains of quality of life [6, 7]. The definition of quality of life varies depending on the disciplinary field in which it is examined. In fact, more than 100 definitions have been presented in the literature so far [8].

One of the promoters of the concept of the quality of life is the European Union (EU), whose assessments of quality of life in the EU and its Member States are based on statistical measurements conducted by Eurostat, the EU statistical office [9]. The EU main objective is to "promote the well-being of its citizens", which is why data on subjective life satisfaction in the EU are collected and analysed annually. The Organisation for Economic Co-operation and Development (OSCD) uses more than 80 indicators and demonstrates improvements in life satisfaction alongside persistent inequalities in its "How's Life?" programme [5].

Another example is the Quality of Life Index (QoLI), launched by the United Nations Human Settlements Programme (UN-Habitat) in 2023. This is an analytical framework designed to help cities understand and improve everyday urban living conditions. The QoLI assists cities in measuring and improving both the objective conditions and the subjective experiences that define urban well-being. The index examines how well a city serves its residents and provides a measure of progress from a people-centred perspective. Embedded within the UN-Habitat Strategic Plan (2020–2025), which prioritises improved quality of life in an urbanising world [10], QoLI operationalises a people-centred approach to urban evaluation at the city level. Structured around nine thematic domains, QoLI integrates global- and local-level indicators to assess quality-of-life outcomes, identify priority areas, and translate empirical evidence into planning strategies and policy interventions [11]. Each domain is evaluated through a dual-indicator structure, combining global indicators that enable cross-city comparisons with local indicators that capture city-specific needs and priorities. Although both systems are designed for implementation at the urban level, *in situ* application remains a challenge.

The aim of this research is to illustrate this process by presenting the implementation of the QoLI in Kragujevac, Serbia. The city was one of approximately 20 global "city pilots" within the UN-Habitat programme conducted in 2025. The process is presented through all stages of the QoLI implementation, including various forms of urban participation: information and communication tools, stakeholder meetings, co-creation mechanisms, and a comprehensive online survey conducted with citizens. Such an approach enables the formulation of a final Quality of Life Index for the city. This index is important not only for enabling comparison between Kragujevac and other pilot cities, but also for generating qualitative inputs to inform and adjust local policy documents and the city budget in response to the most significant findings identified through the QoLI process at the local level.

2 Methodology

This research integrates the elements of theoretical preview and a case study. The theoretical fundamentals about the quality of urban life are already explained in the introductory section. The second part is about the application of the QoLI process in Kragujevac,

which is basically a single-case study. A focus on single case has some noticeable differences to studying several cases. In the former one, there is no option to compare different cases in order to obtain respectable results. Hence, single-case study requires well-structured elements extracted from theory to be evaluated by analysing the case [12]. The QoLI exactly supports this approach with its structured rules for concrete *in situ* application. The final inputs from the QoLI process are gathered from this global-local analysis. These inputs are twofold; (1) some of them were unexpected and they are therefore important at local level, to (re)direct the future urban development and policy, while (2) the other ones are critical to compare Kragujevac at an 'international stage', with other city-pilots. Both elements are highlighted at the end of the research.

3 Local Context – Kragujevac, Serbia

Kragujevac is the fourth largest city in Serbia. By the last national population census from 2022, the administrative territory of the city has 171,000 inhabitants, of which about 85% live in its urban part [13]. The city is in the middle of Serbia, in centrally located Šumadija Region (Fig. 1).



Fig. 1. (left) The skyline of central Kragujevac (Author: B. Antonić, 2025).



Fig. 2. (right) Cannon factory in Kragujevac from 1873, the oldest preserved industrial building on the Balkans, currently under state protection as an industrial heritage (Author: B. Antonić, 2025).

Kragujevac is seen as a "cradle" of modern Serbia at national level. However, the area of Kragujevac has been inhabited since prehistory, despite the city 'golden age' is related to modern times. The settlement was relatively small and unknown until the early 19th century, when the area around Kragujevac was the focal place of two Serbian uprisings against foreign Ottoman rule. This occasion was critical to position Kragujevac as the first capital of modern Serbia. The city was the capital of the Principality of Serbia in the period 1818–1841. During this period many "national firsts" happened in Kragujevac – the first professional theatre, the first museum, the first grammar school, etc. [14].

After the transfer of national capital to Belgrade, Kragujevac became the first industrial centre of Serbia, as well as on the Balkans. The canon factory was established in

1853, while the oldest preserved industrial building was from 1873 (Fig. 2). The industrial complex was significantly expanded in the early 20th century. However, the zenith of the city industry was during the second-socialist Yugoslavia (1945–1992). During this period, "Crvena Zastava" was formed as the main automobile-producing socialist factory of the country. The rapid industrialisation led to the demographic boom of Kragujevac [15]. This fast urban development was stopped with the post-socialist transition in the 1990s, when industrial sector collapsed. The last 15 years have been marked by the reindustrialisation of Kragujevac; nevertheless, this is still far away from the previous glory.

4 Quality of Life Initiative in Kragujevac

The QoLI procedure in Kragujevac was based on the main guidelines by the programme. The essence of the QoLI refers to the adequate application of the UN Sustainability Development Goals (SDGs) in local urban policy so as it facilitates (the rise) of the quality of local life. This can be obtained only by using innovative, globally important vs. locally implementable evaluation system. The main application guidelines of the QoLI are [11]:

- The ultimate goal is to calculate the cumulative QoLI value – a numerical index of the local quality of life.
- Such a goal can be achieved by applying five QoLI principles, by which the process had to be (1) human centric, (2) co-creative, (3) globally relevant while locally applicable, (4) inclusive and (5) evidence-based.
- The QoLI process relies on measuring indicators. There are two types of these indicators global- and local-layer ones. 29 global indicators are applied in all implementing cities. Local indicators – min. 12 of them – had to be developed locally, through urban participation.
- All global-layer indicators are organised in nine domains: (1) basic services & mobility, (2) culture & recreation, (3) economy, (4) education, (5) environment, (6) governance, (7) health & well-being, (8) housing, and (9) social cohesion. The formation of local-layer indicators can follow the same structure.
- Each indicator uses one of four types of data: statistical data, geodata, mobile ping, and data from social-media survey.
- Most of measured values for indicators must be "normalised", to be comparable to the values of other indicators, as well as to values for the same global indicators for other QoLI cities.
- The final QoLI index is an average of measured values for all indicators. As such, it can be easily compared with other cities included in the QoLI.

5 Urban Participation in Quality of Life Initiative

Citizen participation has become an imperative in any process related to urban development today, but it is still an operational challenge [16]. Its main aim is to enable local community to jointly participate, create, and shape desired socio-economic urban policy [17]. However, dynamics and modes of urban participation can vary greatly and

should be adapted to local needs and objectives. New observations show that combining offline and online participatory techniques are more and more common [18]. Generally, it is recommendable to: (1) alter between phases which are more directive and more free-minded; (2) adapt the process to local conditions; and (c) to set up local process which can be comparable to the other ones [19]. These recommendations were basically applied in the QoLI process in Kragujevac. The QoLI prescribed several types of urban participation to be implemented step by step, plus some were added to ensure more community-based decision making.

The first step was an inception meeting for stakeholders, which was held online on April 8, 2025 (Fig. 3). 15 local and regional stakeholders were presented. The main purpose of this first participatory event in the QoLI implementation is to provide stakeholders with a clear overview about the QoLI framework and activities and how they can successfully participate in it. Thus, the inception meeting had a clear format based on the PPTX presentation in mother tongue (in Serbian), which was followed by the stakeholders' comments about if they understood the QoLI basics.



Fig. 3. (left) An inception meeting held online on April 8, 2025 (Author: B. Antonić, 2025).



Fig. 4. (right) The first stakeholder workshop held in person in Kragujevac on April 23–24, 2025 (Author: J. Stefanović, 2025).

The second step – the first stakeholder workshop on April 23–24, 2025 – was diametrically different that the first one, as it was organised in person and in a more open atmosphere (Fig. 4). The workshop had a format of a focus group and about 30 stakeholders took part in it. Its topic was the process of a jointly decision about the urban indicators the evaluation of which would adequately represent local quality of life. Although this workshop was divided into four sessions, they only had general topic and related explanations, while all other elements were free for discussion. This participatory environment proved to be good, so discussions were long and fruitful.

The third step in local urban participation was introduced by local team implementing the QoLI in Kragujevac. The first stakeholder workshop resulted in more prospective indicators than expected. Therefore, this step was added, to complete the selection of local indicators, with a special intention to determine those ones that would be measurable and applicable. The form of an e-survey with an e-questionnaire (Google Forms) was considered efficient in this case. The majority of the stakeholders present at the first workshop responded and fulfilled the e-survey. The e-survey was obviously more

directive than the workshop, but stakeholders already had good insight in the QoLI and understood the purpose of this additional step.

The fourth step was probably the most directive one. It was another survey, but this one was conducted among citizens as it was prescribed in the QoLI guidelines. The survey covered the subjective indicators about the local quality of life, i.e., it was arranged to measure them. Moreover, it had a relatively rigid format of closed questions, although the last possible option in all questions was to skip answer. The reason for this approach was due to its aim to have a good sample of respondents, i.e. to be mass applied. In total, 1,336 Kragujevac inhabitants (>1% of adult city population) completed this survey during August 2025. To achieve this sample, the survey was conducted both offline, on city streets (Figs. 5 and 6) and online, through SurveyMonkey application promoted by the city press and social media. Obtained local responses were critical to measure subjective- and quality-based indicators in the QoLI process.

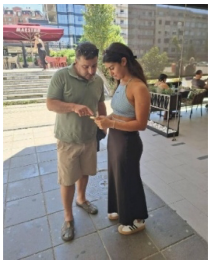


Fig. 5. (left) A survey with citizens on streets in Kragujevac, held in August 2025 (Author: I. Radulović, 2025).

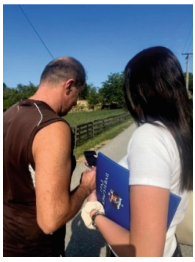


Fig. 6. (centre) A survey with citizens on streets in Kragujevac, held in August 2025 (Author: I. Radulović, 2025).



Fig. 7. (right) The second stakeholder workshop held in person in Kragujevac on November 5, 2025 (Author: J. Stefanović, 2025).

The fifth and last step in urban participation during the QoLI process was on November 5, 2025, on its end. It was organised after measuring all the indicators of the quality of life in Kragujevac. This was the second stakeholder meeting, again held in person in Kragujevac (Fig. 7). Its main objective was to check the whole process and, especially, measured values for all analysed indicators by stakeholders. Aside of this, the its purpose was also to make stakeholders aware of the results and importance of the entire QoLI process and eventually apply them in the future policy development in Kragujevac. Approximately 25 stakeholders were presented at this workshop.

Apart of these more concrete participatory activities, the City of Kragujevac also implemented more 'passive' modes of urban participation in the form of information for citizens through general media, by posting press releases and news about the conducted activities and the QoLI through the official media channels and other communication tools. All in-person QoLI activities were also covered by general media teams, too.

6 Conclusions – From Extreme Outcomes to Shaping the Future Urban Development

Measuring the local quality of life as a paramount input for good urban planning and development. It thus requires a well-organised and comprehensive approach. In line with this, citizen participation in this process also had to be systematically organised, using the different means of participation to accommodate contact to and reactions from the wider scope of local population. The Quality of Life Initiate as global programme exactly utilised this approach, which was implemented.

The QoLI implementation in Kragujevac in 2025 illustrates these diverse approaches. First, it applied the offline/in-person and online modes of participation, further employing outdoor in-person participation on city streets. An advantage in this case is also that these two modes were also altered to enable a more dynamic process.

Second, the QoLI application in Kragujevac also adopted the alteration between more directive and more free-minded steps in participation. This approach allows the fine tuning of the ultimate goals of the QoLI process; (1) to form the list of local indicators as a more free-minded process with stakeholders, who are professionally more involved in this topic, with (2) measuring these indicators by working with wider pool of participants (local population) as more a directive step.

To enable this alteration, the whole process was first adapted to local conditions, in the first half of its duration (March–June 2025). This was also a part of online training done by the central QoLI office through webinars, as well as given in all QoLI guidebooks. The Kragujevac team furthermore customised the participatory process to local conditions by adding a new step (Google Form Survey) when it realised that this addition was necessary.

The last conclusion about the possibility to compare urban participation in the Kragujevac case with the other ones is also interesting, as it is in the essence of the QoLI Programme. The QoLI was globally established to facilitate the comparison and joint work of included cities across the globe by measuring the quality of local life. 29 QoLI indicators are set up by the programme as global-layer ones, i.e., to be analysed and measured in each city so to be comparable worldwide. After completing the QoLI in Kragujevac, obtained values for all indicators, as well as the cumulative index of the quality of local life, were posted at the QoLI main website with the same ones for other cities which passed through this process. In this way, the comparison of included cities is even accessible to everybody all over the World as each city can easily understand its position in wider network.

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Bridging Nature-Based Built Environments, Circularity, and Passive Performance: A Regenerative Case Study for Sustainable Learning Environments in Crete

Theodora Kyriafini[1(✉)], Fotini Lymperiadou[1], and Nikolaos Protogeros[2]

[1] euZen Architecture, Thessaloniki, Greece
info@euzenarchitecture.com
[2] Polygyros, Greece

Abstract. This paper explores pathways toward a regenerative built environment through the case study of the Innovative Bioclimatic School of European Education in Crete. It presents a whole-lifecycle approach that links research and practice by integrating nature-based design, circular material development, and validated passive systems, forming a "didactic instrument" for environmental education.

An integrative design process reinterpreted the vernacular Mediterranean courtyard typology. Sustainable operation was optimized through simulation (CFD, IES-VE, ENVI-met, Climate Studio) to validate passive strategies including Trombe walls, winter gardens, controlled thermal mass, natural vertical and cross-ventilation, daylight optimization, and microclimate modulation through vegetation and water features. Concurrently, a circular construction methodology involved research (Aristotle University) to develop stabilized Compressed Earthen Blocks (CEB) using excavated site soil and hemp fibers, supplemented by other natural materials such as Cretan limestone and timber.

Final design-stage simulations indicate strong performance, including a 51.1% LEED energy-cost reduction compared with the ASHRAE 90.1–2010 Appendix G baseline, including renewables, and compliance with ASHRAE 55 thermal comfort criteria. The nature-based design delivered 79.7% spatial Daylight Autonomy and 94.9% Quality Views. The circular material research was supported by laboratory testing: the CEBs achieved 6.77 MPa compressive strength and contributed to passive indoor humidity regulation (50–55% RH). A closed-loop water system with constructed wetlands supports regenerative operations.

This best-practice case study provides a replicable model for Sustainable Buildings. It demonstrates how synergies across scales—from nature-based design and passive environmental performance to circular material science—embed actionable sustainability and enable a regenerative trajectory for future public buildings.

Keywords: Regenerative Design · Bioclimatic Architecture · Circular Economy · Earthen Blocks (CEB) · Nature-Based Built Environments

N. Protogeros—Independent Consultant

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1 Introduction

The "Innovative Bioclimatic School of European Education in Crete" (Fig. 1) was awarded 1st prize in an International Architectural Competition (2012) under UIA and SBO auspices. Located on a 15,748 m^2 plot within the Heraklion University Campus, the 7,600 m^2 complex accommodates 780 students for Kindergarten, Primary and Secondary Education.



Fig. 1. Southeast and southwest perspective view of the school complex.

The design leverages local climatic data, integrating traditional Mediterranean courtyard typologies (Fig. 2) with advanced passive strategies to promote student well-being and environmental sustainability. Connection with nature acts as a catalyst for learning and experiential sustainability education. The project completed the final detailed design at the end of 2025; therefore, the reported results are design-stage predictions. In 2026, the project tendering process is being carried out.



Fig. 2. Courtyards of Kindergarten, Elementary School (top), and Secondary School (below).

2 Integrated Methodology and Design Interaction

The regenerative design is a synthesis of components and parameters, all connected like communicating vessels in equilibrium. Environmental design reinforces education and awareness, natural materials promote a healthy environment and passive performance strategies teach an awareness on nature's wisdom.

Contextual Analysis: Site-specific climate data, orientation, topology, educational use, soil composition (clay), local materials (limestone), ancient courtyard archetypes, informed the initial design parameters.

Material Performance: Laboratory testing at Aristotle University on stabilized Compressed Earthen Blocks (CEB) made with site-excavated clayey soil and hemp fibres achieved a compressive strength of 6.77 MPa. These results informed the material assumptions used in the simulations. The 30 cm "hyper-thick" walls ensure high indoor air quality and humidity regulation. These locally manufactured, low-embodied energy blocks remain exposed or clay-plastered, creating a "breathing" building envelope for the Kindergarten (Fig. 3).



Fig. 3. Earthen Block Wall in the Kindergarten's Multi-purpose Hall and Earthen Blocks from laboratory tests with hemp fibers.

Integrated Simulation: IES-VE was used for energy and thermal comfort analysis; ClimateStudio/Radiance and Ladybug Tools for daylight, solar and comfort post-processing; ENVI-met for outdoor microclimate; OpenFOAM for wind movement; and Archiwizard, COMFEN, THERM and DesignBuilder for façade, thermal and environmental design support (Fig. 4).

Validation: Simulation outputs led to the refinement of the passive systems (winter gardens, Trombe walls, vegetation placement) being implemented in the construction phase.



Fig. 4. Southeast perspective view of the school complex: IES-VE energy study model and courtyard lighting diagram, showing the placement of low-rise buildings to the south.

3 Passive Performance Strategies

3.1 Solar and Thermal Management

The Mediterranean courtyard typology is central to the design, utilizing narrow building depths to ensure 100% south-facing orientations for maximum winter solar gain (Fig. 5).

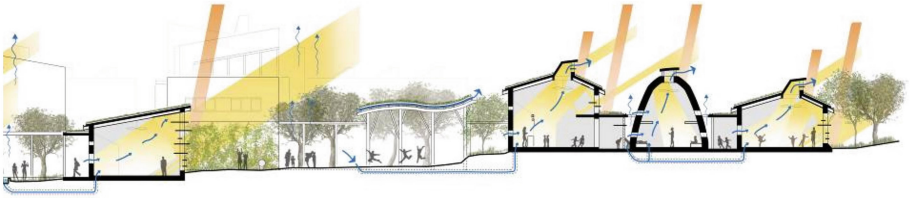


Fig. 5. Section of the school complex showing summer-winter solar radiation and natural cooling via the stack effect.

Thermal Mass: High-capacity materials, including exposed CEBs and fired bricks, minimize indoor fluctuations.

Passive Heating and Cooling: Beyond direct gain, winter gardens and insulated Trombe walls/air collectors on southern facades ensure immediate heating (Figs. 6 and 7). Trombe walls play a role in cooling in the summer months as well.



Fig. 6. Winter gardens and operation diagram (right) showing winter and summer.



Fig. 7. Trombe walls in the Science Laboratories: exterior view in summer with open skylights; interior view with closed insulated shutters; and operation diagram for winter and summer.

3.2 Cooling and Natural Ventilation

Natural cooling is achieved through vertical and cross-ventilation via 'stack effect' with roof skylights acting as cooling chimneys and north-facing low-level windows, night cooling of thermal mass, and strategic shading (Fig. 8). Advanced simulation software (Ladybug Tools, Radiance, ClimateStudio, Archiwizard, OpenFoam, IES-VE, and DesignBuilder) was used to analyze solar/shading, air movement, and thermal behavior (Fig. 9A).

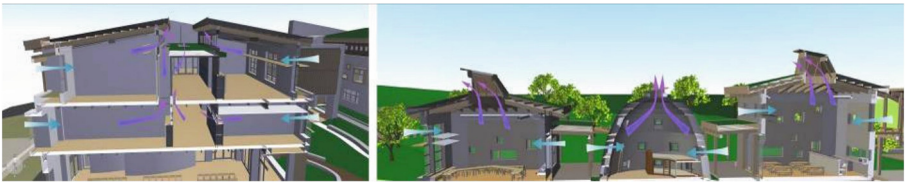


Fig. 8. Natural ventilation for classrooms in the Secondary School and Kindergarten.

3.3 Thermal Comfort and Energy

Dynamic simulations using **IES-VE 2023** validated the school's performance against ASHRAE 55–2010 (Fig. 10B).

Energy Reduction: The design achieved a 51.1% reduction in energy consumption compared to a baseline model (Fig. 10B, C).

Thermal Compliance: Simulations indicated compliance with ASHRAE 55 criteria. Passive and mixed-mode strategies reduce cooling reliance in teaching spaces, while active cooling remains included for offices and multipurpose spaces (Fig. 10).

3.4 Circular Materials

Internal walls utilize high thermal mass to stabilize indoor temperatures. Specifically, the Kindergarten features non-bearing walls made of CEBs developed from excavated site soil.

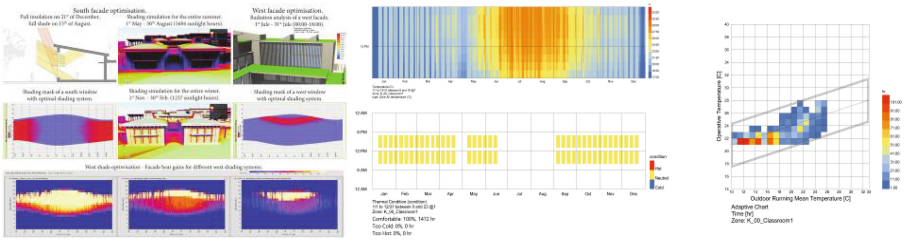


Fig. 9. A. Optimization simulations for southern, eastern, and western facades and openings, using Ladybug Tools, Archiwizard, and COMFEN. B. Adaptive thermal comfort results for a primary classroom throughout the year, using IES-VE and Ladybug Tools software.



Fig. 10. A. Dynamic thermal simulation. Gains and losses for December. B. Results with consumption of 1 kWh/m^2. C. Results showing that during sunny days, heating is not necessary.

Hygroscopic Regulation: CEBs maintain indoor relative humidity between 50–55%, mitigating the extreme fluctuations (20–70%) found in conventional buildings.

Embodied Energy: By using local clay, hemp fibers, and Cretan limestone, the project minimizes transportation emissions and ensures 100% recyclability at end-of-life.

4 Environmental Quality and Biophilic Design

4.1 Lighting and Visual Comfort

ClimateStudio/Radiance simulations predicted 79.70% sDA and 4.20% ASE, meeting the LEED v4.1 daylight criteria; movable shading is included where local ASE risk remains (Figs. 11 and 12). Quality-view analysis indicated 94.9% compliance with LEED v4.1 criteria (Fig. 12C). Strategic layout and opening design integrate biophilia (Qiannan Guo, 2024) to enhance user well-being (Fig. 11C).

4.2 Microclimate Modulation

ENVI-met simulations predicted improved outdoor comfort compared with a typical Greek school with conventional construction materials and a low-vegetation baseline, across winter, summer, and intermediate seasonal scenarios (Fig. 13). This is achieved through Vegetation: Green roofs and endemic planting, and Water Elements: Shallow ponds and streams for evaporative cooling (Fig. 14).

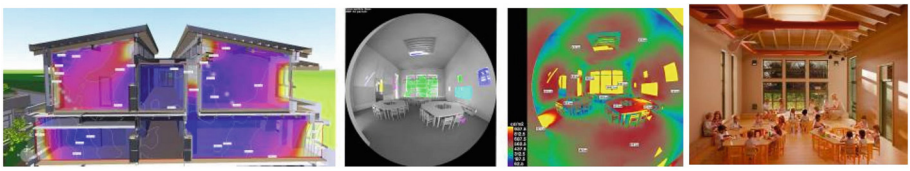


Fig. 11. A. Natural lighting simulation results for Secondary School spaces, B. Glare study for a Kindergarten space, September 21st, using Archiwizard and Ladybug Tools/Radiance software and C. The Kindergarten classroom.



Fig. 12. A. Natural lighting simulation results (sDA), B. Sunlight results (ASE), C. Simulation results for quality of view conditions using ClimateStudio software.

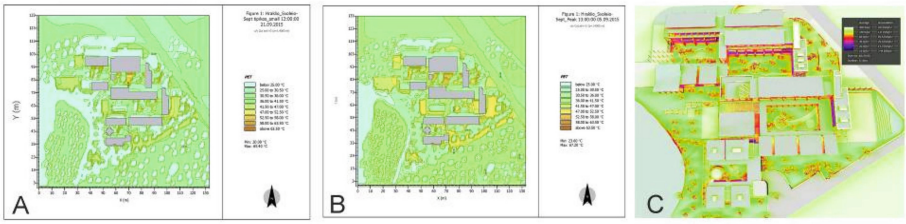


Fig. 13. Results of simulations with Envi-met and ArchiWizard. A. PET thermal comfort index, Mean September conditions, 13.00, B. PET thermal comfort index, Peak September conditions, 13.00, C. Detailed solar radiation analysis 1–31 July.



Fig. 14. Ponds, streams and planting in the surrounding area.

Wind Protection: ENVI-met indicated winter reduced local wind exposure, while OpenFOAM was used separately to assess wind movement around the building massing, optimizing the seasonal use of outdoor "didactic instruments" (Fig. 15).

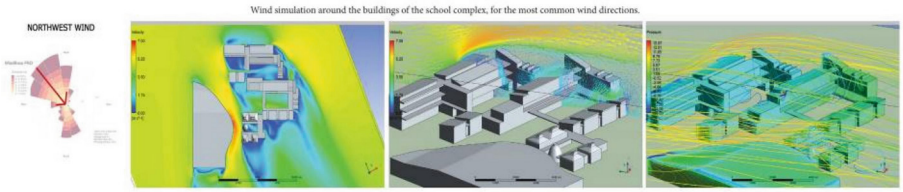


Fig. 15. Wind movement simulation images (OpenFoam) of the main air directions.

5 Discussion: Transferability and Lessons Learned

Climate Dependency: While optimized for Crete's high solar radiation and summer breezes, these principles may be adapted to other public buildings where climate, materials and regulations allow. Replication in Northern Europe would require adjusting glazing ratios and insulation thicknesses while maintaining the core principles of circular material use. The integration of a BEMS to automate active and passive synergies (e.g., night cooling skylights) remains a critical lesson for achieving 50% energy savings compared to conventional baselines. **Material Availability:** The circularity of the CEBs depends on soil composition; silty or sandy soils would require different stabilization agents than the Cretan clay used here. **Regulatory Barriers:** A major challenge was the certification of non-standard materials like earth blocks within public procurement frameworks, a lesson for future public projects.

6 Conclusion

The Innovative Bioclimatic School in Crete demonstrates that regenerative performance is achievable through the synergy of vernacular wisdom and advanced simulation. It exemplifies a regenerative trajectory where architecture serves as a "didactic instrument" for sustainability. By synchronizing circular material science (CEBs) with bioclimatic interventions (Trombe walls, winter gardens, courtyards), the project achieves exceptional energy efficiency and psychological comfort, offering a standardized methodology for future healthy educational environments.

This case study offers a reference for future educational buildings, showing how nature-based and circular strategies can support substantial energy-cost savings and improved comfort.

Interdisciplinary Design Team

Architectural Study: THEODORA KYRIAFINI – FOTINI LYMPERIADOU & CO. L.P./"euZen Architecture"

T. Kyriafini, F. Lymperiadou, K. Despotidis, I. Despotidis, A. Efthymiadou

Associates: R. Tsitouridou, C. Saxoni, E. Malezi, A. Iosifidou, F. Rizou, E. Kefalloniti, M. Ioannidou - 3D Visualization: N. Kantidakis, P. Galanis

Environmental Design Consultants: N. Protogeros, X. Zisis/**Planting Design**: Nasia Kikidou, T. Zangas, T. Zanga, N Misyrlis/**Acoustics Consultants**: G. Schubert, N. Tsinikas

Structural Study: OMETE S.A., K. Kalatzi, M. Tsitsi, K. Chatzopoulos, I. Lepidas - I. Spinasas L.P. Associates: N. Sakellari, T. Tsantekidou/**Electromechanical Study**: SKEMMA ENGINEERS P.C./**Biochemical Installations Study**: A. Dermetzoglou

Laboratory Analysis of Earthen Materials: Laboratory of Building Materials, AUTh Department of Civil Engineering/Scientific Lead: I. Papayianni.

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Reframing Building Envelope Design for Durability and Health in a Changing Climate

Natalia Saavedra Toro[1(✉)], Eugenia Gasparri[1], Aysu Kuru[1], Alberto Sangiorgio[2], and Arianna Brambilla[1]

[1] School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW 2006, Australia
natalia.saavedratoro@sydney.edu.au
[2] Arup, Sydney, NSW 2000, Australia
natalia.saavedratoro@sydney.edu.au

Abstract. Climate change is intensifying extreme weather events and elevating temperature and humidity, increasing moisture risks in buildings, including condensation, mould growth, and material degradation that threaten durability and occupant health. Despite mould affecting an estimated 10–50% of dwellings globally, moisture management remains insufficiently addressed in housing design and construction. This study reframes building envelope design for moisture resilience through a critical review of best practices and hygrothermal performance assessment methods. Considering environmental and design factors, it progresses from evaluating conventional moisture-control practices to emerging technologies, including vented cavities, airtight construction, and detailing strategies, assessing their influence on moisture ingress and long-term performance. Findings show traditional design and construction practices that follow conventional assessment methods and regulatory standards are insufficient to ensure moisture resilient envelopes. An integrative approach combining improved detailing, adaptive materials, and proactive monitoring would support extending building life cycles. Responsive façade systems are highlighted as promising for long-term performance under changing conditions. Advanced solutions including smart coatings, moisture-adaptive sealants, self-healing materials, moisture-responsive ventilation systems, and IoT-enabled sensors offer strong potential to improve buildings durability and to withstand climatic stressors such as floodings. In response, this study proposes an integrative, climate-responsive five-layer framework linking (1) climate and exposure characterisation, (2) assessment method selection, (3) envelope strategy and materials, (4) junction detailing and constructability, and (5) monitoring, operation, and intervention. By reducing moisture-related failures and premature refurbishment or replacement, the framework supports longer service life and contributes to circular, lower-impact building outcomes through life extension and improved resource efficiency

Keywords: Climate Responsive Design · Moisture Resilience · Climate Resilience · Building Durability · Mould Growth Risk · Responsive Facades

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1 Introduction

Climate extremes are intensifying the hydrological cycle, raising absolute humidity, wind-driven rain, and heavy precipitation [1]. These changes increase walls' exterior wetting and moisture ingress while constraining envelope drying, thereby elevating the probability of interstitial condensation, persistent dampness, and mould growth, with increased risks to material durability and occupant health [2].

The scale of moisture issues is already substantial. The World Health Organization reports that indoor dampness is estimated to affect 10–50% of indoor environments across Europe, North America, Australia, India, and Japan [3]. Dampness and mould are consistently associated with adverse health outcomes, including exacerbation of asthma, allergies, and respiratory infections [4]. Beyond health, excess moisture accelerates materials degradation, compromises structural integrity, reduces thermal resistance, increases energy use and elevates chemical emissions from building materials and furnishings [5], thereby, further degrading indoor environmental quality. Despite this evidence, moisture management remains insufficiently integrated in design workflows and regulatory frameworks, which still favor prescriptive provisions over proactive, integrated strategies. In Australia, both surface and interstitial condensation have affected buildings for decades. Studies link these issues in part to the strengthened energy-efficiency provisions in the National Construction Code, while acknowledging that other factors also contribute [6]. As insulation levels increase and envelopes tighten, indoor moisture loads and mould risk also rise unless airtightness is explicitly paired with adequate ventilation and moisture control measures [7]. Given these challenges, there is a pressing need to reframe building-envelope design to withstand moisture risks. This study reviews conventional and emerging approaches to moisture control in building envelopes and opens a discussion to guide durable, health-oriented design.

2 Research Methodology

This study undertook a structured literature review on conventional moisture-control strategies, hygrothermal assessment methods, and emerging moisture-resilient technologies. Searches were conducted in Scopus using targeted keywords (for example, moisture control, building envelopes, rainscreen/vented cavity, condensation, mould growth, hygrothermal/HAM, WUFI/DELPHIN, and terms associated with relevant standards and protocols). Records were screened in stages (duplicate removal, title and abstract screening, then full-text review), retaining only peer-reviewed journal articles directly relevant to envelope moisture performance and assessment. No exclusions were applied solely on geography or climate; instead, climate context was noted where reported to support interpretation. The search yielded approximately 80 relevant studies, from which a subset of approximately 25 is presented and discussed in this paper across the three thematic areas. The review is complemented by the authors' earlier studies [8–10], which provides empirical evidence and supports the discussion on moisture-resilient envelope design.

3 Findings

3.1 Conventional Moisture-Control Strategies

Conventional moisture strategies in building envelopes rely on several construction components. Some of these include the application of weather-resistive barriers and vapour-control layers, designed to deflect liquid water and to limit water-vapour diffusion through assemblies [7], however effectiveness depends on continuous detailing, correct installation, and construction quality control at flashings, membranes, and sealant systems [7, 11]. Placement of vapour barriers or retarders is climate- and drying-path dependent (typically interior in cold climates and exterior in warm-humid climates) and must be coordinated with drainage and ventilation, ensuring at least one reliable drying pathway to avoid trapping moisture within the assembly [12]. Prior empirical testing by the authors showed that unventilated cavity air gaps in cold-temperate climates (including climate zones 22 and 62 in Victoria, Australia) exhibited mould growth risk when assessed using ASHRAE 160 and DA07 protocols. Introducing cavity ventilation substantially mitigated this risk, reducing predicted mould growth by more than 99% relative to non-vented conditions [8, 9], as shown in Fig. 1. Drained and ventilated rainscreen assemblies, incorporating a continuous ventilated cavity between cladding and the weather-resistive barrier, reduce interstitial condensation by limiting wind-driven rain, creating a capillary break, and enabling drainage and convective drying [13] with performance contingent on ventilation rate, cavity dimensions, climate, and robust detailing [14]. However, this performance can be challenged under elevated moisture exposures, such as flooding or intense rain events. In the authors' empirical work [9], an additional external moisture load was applied to a tiled roof assembly to represent intense rainfall (in addition to the standard 1% rain load per DA07), and the results showed that increased rain loads elevated moisture risk in the tiled roof type, which had previously presented low mould-growth risk under standard conditions.

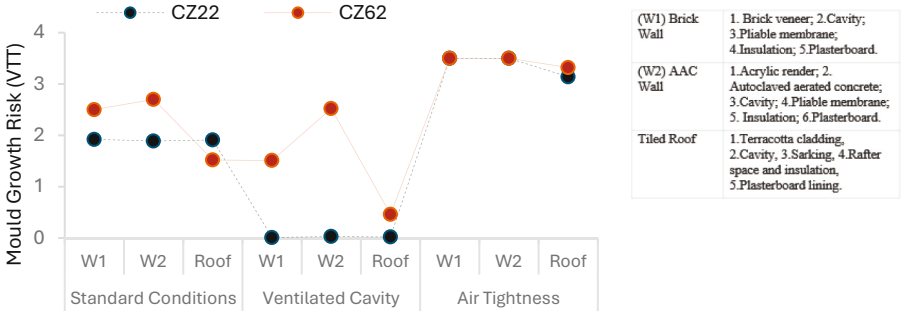


Fig. 1. Mould growth index (VTT) reproduced from the authors' previous work [8, 9] for three assemblies across two climate zones (CZ22 and CZ62), representative of Victoria, Australia under three Scenarios: (i) Standard conditions, based on ASHRAE 160 and AIRAH DA07 criteria with unventilated cavity; (ii) Ventilated cavity, constant cavity ventilation at 25 ACH (ACH = Air changes per hour); (iii) Airtight envelope, building ACH = 0.25. VTT results are reported at the insulation–membrane interface (towards the exterior) for each assembly.

Risk factors that can compromise conventional moisture-control strategies include insulation selection and airtightness. The authors' empirical testing and simulations [10] indicate that, in temperate climates, timber-framed walls with synthetic PIR[1] exhibit medium mould-growth risk, whereas mineral and natural insulation show near-zero risk, highlighting the influence of insulation type. Higher insulation levels also require careful coordination with vapour control, since shifted dew-point locations and reduced incidental drying can increase mould risk [15]. In terms of airtightness, if not balanced with adequate ventilation, it can elevate indoor humidity. Consistent with this, Fig. 1 shows that increasing airtightness to 0.25 ACH led to a further rise in mould-growth risk across all assemblies, reaching a mould index of 3.5 under the ASHRAE 160 protocol.[2]

3.2 Hygrothermal Assessment Methods

The hygrothermal assessment methods discussed here focus on those most commonly applied in practice, ranging from steady-state approaches to computational tools, selected according to their capacity to represent increasingly complex moisture-transport phenomena. Simplified, steady-state approaches, such as the Glaser method referenced in ISO 13788, evaluate steady-state heat conduction and vapour diffusion, however, do not account for transient effects [7]. In contrast, numerical simulation tools and transient HAM models (e.g., WUFI Pro, DELPHIN, and related platforms) simulate coupled heat, air, and moisture transfer under time-dependent boundary conditions; WUFI Pro is widely recognised and has been validated against the EN 15026 framework [16]. To resolve localised risks, two-dimensional simulations (e.g., WUFI 2D) can identify weak points where heat and moisture fields are non-uniform, particularly at construction details such as junctions and interfaces, providing insight that are not available in one-dimensional analyses [17]. To address gaps in simulation boundary conditions, particularly incomplete indoor-climate data and material properties (for example, water-vapour diffusion parameters), empirical field monitoring and testing of temperature, relative humidity, and moisture content within assemblies provide real-world datasets for calibrating and validating simulations, thereby improving the reliability of model parameters and assumptions [10]. In parallel, accounting for variability in transient assessments is essential: moving beyond conventionally adopted assessment methods to incorporate predictive climate scenarios and project-specific indoor conditions captures the wider range of real-world exposures that assemblies are likely to encounter, and improves the robustness of moisture-risk appraisal [9].

3.3 Emerging Moisture Resilient Technologies

As buildings face increasingly frequent and severe climatic conditions, supplementary strategies are needed to safeguard long-term durability, reinforcing the case for advanced technologies that augment, rather than replace, conventional moisture-control

[1] PIR = Polyisocyanurate insulation panels

[2] Hygrothermal Performance Criteria: VTT Mould Growth Index (MI). Low Risk M1 < 1; Medium Risk $1 <$ MI < 3; High Risk M1 > 3.

approaches. In this context, emerging technologies can be integrated alongside conventional moisture control methods to enhance water shedding, maintain seal integrity, accelerate drying, and provide early-warning diagnostics as follows:

Smart coatings and surface treatments, can include nano-modified hydrophobic treatments for exterior concrete that enhance moisture resistance and durability [18], and inorganic mineral coatings (carbon-absorbing) for concrete and masonry that offer high bonding strength with reduced capillary uptake [19].

Moisture-adaptive sealants and barriers can range from water-resistive barriers with humidity-responsive permeance that respond to wetting and drying in wall systems [20], to hydrogels for adaptive façade skins that provide high moisture buffering, with strong absorption and release cycles [21], and hygromorphic materials that are responsive to humidity for smart moisture regulation [22].

Self-healing materials address durability at the source of damage. Lime and lime-based plasters for wall and ceiling applications, provides moisture buffering and natural self-healing of microcracks [23]. Self-healing cementitious systems (microcapsules, bacteria, mineral agents) for renders, mortars, and structural wall layers can seal cracks, recover impermeability, and reduce water ingress through humidity-activated healing [24, 25]; superhydrophobic self-healing wood coatings for timber façades reduce water uptake and maintain hydrophobicity after damage, supporting dimensional stability [26].

Moisture-responsive ventilation provides control at the system level. Humidity-sensitive air inlets and demand-controlled ventilation can reduce energy use, manage moisture loads, and prevent condensation and mould risk [27]; CFD-informed hybrid systems assist in complex contexts such as heritage or underground spaces, providing targeted RH control and optimised equipment placement [28]; moisture-recovery ventilation and heat or moisture exchangers help balance ventilation while recovering energy and improving indoor humidity control [29]. Finally, IoT-enabled sensors support proactive prevention: moisture and humidity sensors enable real-time monitoring and predictive maintenance [24, 30], while leak-detection systems in residential settings facilitate rapid intervention to avoid repair costs and reduce water-related damage [31].

An integrative approach that combines robust detailing, adaptive materials, and proactive monitoring strengthens envelope moisture resilience, prevents damage, extends service life, and supports healthier indoor air quality. Within this approach, responsive façades add adaptability by modulating ventilation or surface behaviour as conditions change, improving performance under climatic uncertainty.

4 Discussion and Conclusion: Towards Moisture-Resilient Envelope Design

Findings from the literature review and the authors' previous empirical work converge on one core point: moisture resilience requires an integrative approach to building-envelope design that is responsive and adaptable to extreme climatic events. The principal contribution of this paper is to open a structured discussion through a practical framework, reframing moisture management from isolated technical measures into a coherent, project-wide decision process that supports durability and health-oriented design across the building life cycle. To support this discussion, Fig. 2, proposes a five-step assessment framework:

(1) climate and exposure characterisation, which establishes the risk profile the envelope must withstand by analysing site conditions such as wind-driven rain and flood risk; (2) assessment method selection, which defines the hygrothermal analysis method in line with the moisture-risk profile, and sets boundary conditions and test scenarios; (3) envelope strategy and materials, which iterates system configurations, such as cavity depths, weather-barrier selection, insulation, surface protection, and adaptive materials; (4) junction detailing and constructability, which evaluates construction details to limit water ingress, applies 2D virtual simulations where appropriate, and defines commissioning tests to verify correct implementation; and (5) monitoring, operation, and intervention, which plans operational monitoring with targeted sensors at critical interfaces, sets alert thresholds and response/intervention protocols, and addresses any issues identified during commissioning.

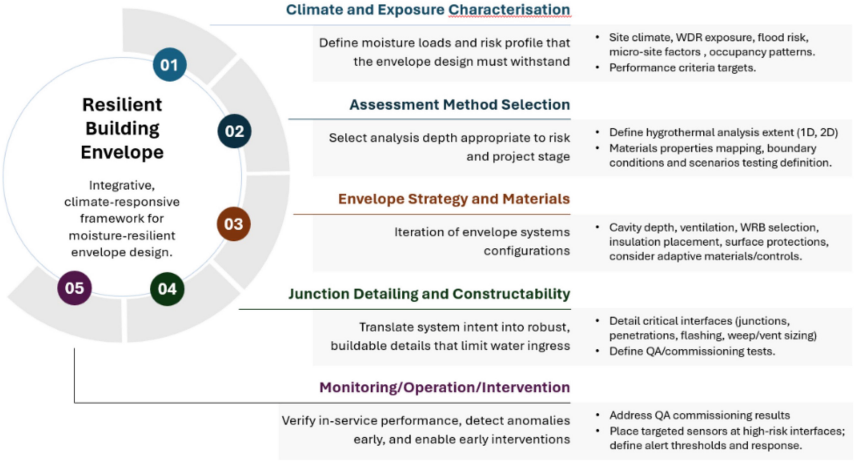


Fig. 2. Integrative and climate responsive assessment framework for moisture-resilient envelope design.

Taken together, these steps propose a route to moisture-resilient envelopes that protect durability and indoor environmental quality under present conditions and extreme climatic events. The framework is intended to guide design decisions and support consistent, verifiable performance from concept through operation.

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Circular Strategies for the Built Environment in Timber: Renovation Scenarios for Traditional Timber Framing Methods

Meriem Rezzag Lebza(✉) and Thomas Haavi

NTNU Norwegian University of Science and Technology, Trondheim, Norway
meriem.r.lebza@ntnu.no

Abstract. This study evaluates insulation retrofits and heat pump installation in an early 1900s dwelling. An air-to-air heat pump provides the greatest single reduction in supplied energy (42.5%), while insulation measures show diminishing returns, especially beyond 10 cm. Combined wall-roof insulation outperforms wall-floor configurations, while additional thickness yields minimal gains once a heat pump is installed. CO_2 analysis over 60 years shows that operational savings decrease as insulation thickness increases, and embodied emissions can outweigh benefits, particularly with repeated heat pump replacements. In a decarbonizing energy system, moderate insulation with efficient heating technologies offers the most effective lifecycle carbon strategy.

Keywords: Timber frame systems · Energy efficiency · Life cycle assessment · Timber construction

1 Introduction

Construction activities account for 36% of global energy consumption and 39% of CO_2 emissions, making the built environment a critical target for decarbonization [16]. Among structural materials, timber offers a compelling alternative to concrete, with studies reporting a 42% reduction in production-stage emissions [18]. However, the environmental benefits of timber are significantly undermined by end-of-life incineration practices, underscoring the importance of strategies that extend building service life rather than accelerating material turnover [19]. This study examines renovation optimization as a strategic pathway to extend the service life of Norway's pre-standard timber housing stock. Buildings constructed before the introduction of building regulations, representing approximately 20% of all houses built in Norway [20], remain outside the scope of current national retrofit guidelines, which are calibrated to modern light timber framing techniques developed after the 1940s [9]. Traditional Norwegian timber construction, exemplified by the Reiseverk typology, differs fundamentally from its modern counterpart in both structural configuration and thermal behavior. Whereas contemporary light timber frames rely on spaced studs that introduce systematic thermal bridges, traditional frames incorporate a continuous wood layer across the facade [9].

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Applying sarendardized modern retrofit specifications with a current recommendation approximating 300 mm of insulation for walls and 150 mm for floors and roofs to these buildings is therefore materially inefficient [17]. Such approaches risk over-insulating structures whose existing thermal mass already confers significant energetic advantages, while failing to account for typology-specific behavior. Typology-sensitive renovation strategies, tailored to the structural and thermal characteristics of pre-regulation timber buildings, offer a more measured and resource-efficient alternative. By optimizing rather than standardizing retrofit interventions, it is possible to extend the service life of this housing stock significantly, preserving embodied carbon.

2 Methodology

By leveraging national geospatial datasets, specifically FKB-Bygning and SEFRAK-Bygning, a comprehensive mapping of the building stock within the designated study area was conducted. These datasets provide critical architectural and historical metadata, including building typology, footprint area, and chronological construction periods.

The analysis integrated both contemporary and historical building inventories, including structures designated under SEFRAK Class 2 protection (those with cultural value but potentially subject to energy retrofitting or regulation). To characterize the residential urban fabric, the dataset was filtered exclusively for the residential building category. This methodology enabled the identification of a representative case study reflecting the most prevalent building characteristics within our regional context.

Due to limited data on contemporary structures, the study analyzes historical buildings by categorizing them by construction volume across time periods (Fig. 1) This temporal distribution helps identify typical structural systems and construction techniques for each era and supports the development of deep-renovation strategies to meet modern standards such as TEK17, Low Energy buildings, Passive House, and Zero Energy Building targets. Preliminary findings show that contemporary buildings are mainly single-family detached houses, while historical stock is dominated by residences and agricultural barns. Most historical buildings date from 1900–1924 and were primarily timber frames with rectangular planks (Fig. 2). (NO: plankerreisverk). These buildings accounted for nearly 80% of new construction by the 1920s, a consequential effect of the introduction of sawmills by the late 1850s [7].

Spatial data of footprint area and perimeter length were mapped to evaluate their bivariate distribution. The calculated median (L: 49,9 m, A: 131,8 m^2) serves as the geometric basis for the case study, ensuring the energy simulation reflects the prevailing building typology within the dataset (Table 1).

- The total percentage of windows (openings) to wall ratio is 16% (single glazing).
- The floor is assumed to be on the ground.
- The walls are assumed to have a continuous layer of wood studs (Reiseverk).
- The roof is assumed to be a ceiling with an unventilated loft (36°).

According to (Holopainen.et al. 2015) in one case study, the primary energy performance in Finnish conventional houses average 330 kWh/m^2 with similar system (electric radiator) and a thermal transmittance of the house envelope of 0,78 W/m^2K.

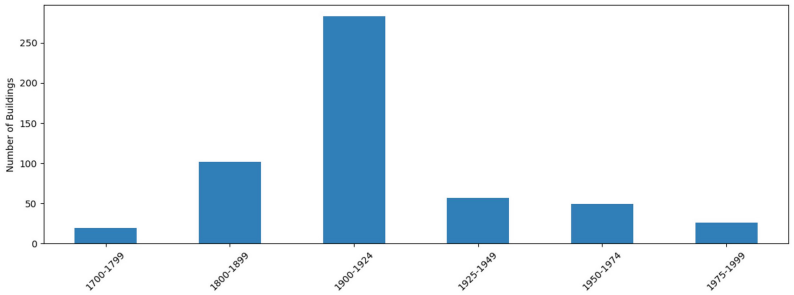


Fig. 1. Historical buildings classified by their construction volume and time period.

Table 1 Composition and thermal transmittance value of components in older timber buildings

Building category	Dimension of exterior wall	U-value (W/m^{2}K)			
		Wall	Roof	Floor	Windows
Wood frame houses built 1890–1928	76 mm (3″) planks + air layer and exterior cladding [8–14]	0.85	0,8	0,96	4,1–4,5

2.1 Study Case and Assumptions

The study case in this paper is assumed to be a single-family residential house built in a period timeframe between 1890–1928. All other assumptions/simulation settings are provided in Table 2 (Table 3).

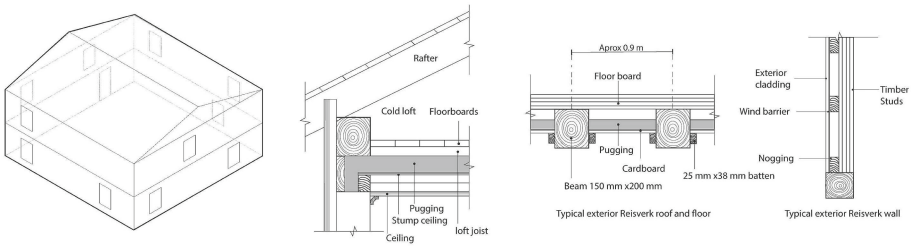


Fig. 2. 3D model of our study case "detached house" (far left) and illustrations of building components for single houses built between 1890–1928 (Byggforsk).

The energy system consists of an air-to-air heat pump [15] sized for residential use with a 15-year service life. Embodied emissions are assessed using a cradle-to-grave system boundary consistent with EN 15978, excluding end-of-life benefits. The primary metric is total lifecycle CO_2 in kg CO_2/m^2 over a 60-year study period, within which the heat pump undergoes three replacement cycles. The embodied carbon of both replacements and added mineral wool insulation is included in all scenarios, ensuring deeper insulation levels are weighed against their upfront emissions. Operational energy

Table 2 Simulation settings parameters

Building volume	625 m^3	Building height: 5 m, footprint:125 m^2
Building envelope	470 m^2	Perimeter: 44 m, number of floors: 2
Heated floor Area	250 m^2	Total of both floors
Windows and doors [6]	16% ratio	11 windows (1 m x 1.5 m) + 1 door (1 m x 2 m)
		Reference case U-value =4.5 (W/m^2K)
		New U-value for upgraded = 0.8 (W/m^2K)
Furniture intensity	N/A	Average furnishing for a house
Ventilation CAV	1.20 m^3/h m^2	Set up to natural ventilation (TEK17)
Thermal bridges	0,07 W/m^2K	The studs are assumed as a continuous layer (TEK17)
Thermal conductivity [2]	0,035 W/(mK)	Typical range for mineral wool
Air leakage [5] q50	3,9 l/s m2	Reference case built in Denmark (similar construction and climate) in 1880 with a footprint of 250 m2
Air leakage [5] n50	10.55 1/h	

Table 3 Thermal transmittance values for different insulation thicknesses

Selected Building category	Adapted U -value for building components [W/m2K]		
	External walls	Floor	Roof
Original U-value (1890–1928)	0,85	0,96	0,8
Addition of 50 mm of insulation	0,391	0,40	0,377
Addition of 100 mm of insulation	0,251	0,25	0,243
Addition of 150 mm of insulation	0,185	0,19	0,18
Addition of 200 mm of insulation	0,145	0,15	0,143

demands are simulated annually in SIMIEN [4], with emissions computed by applying a linearly decarbonizing grid emission factor following NS3720, from $f_{2025} = 0.018$ kg CO_2/kWh in 2025 [3] to $f_{2050} = 0.0$ kg CO_2/kWh by 2050, expressed as:

$$f(t) = f_{start} - \left(\frac{f_{start} - f_{2050}}{2050 - t_{start}}\right) \times (t - t_{start})$$

3 Scenarios

In all cases, the house already has existing heat panels installed. The insulation varies as follows:

Reference basepoint (Electric heating system):

Uninsulated original house + existing Heat Panels

With a heat pump:

Uninsulated original house + existing Heat Panels + Heat pump (set up as a primary source for heating)

Insulated Envelope walls/Roofs/Floors:

Original house + existing Heat Panels +50 mm/100 mm/150 mm/200 mm.

Windows upgrade: Windows according to TEK17 of minimal U value =0,8 W/m^{2}K.

3.1 Results

3.1.1 Energy Mitigation through a Single Application of Thermal Insulation

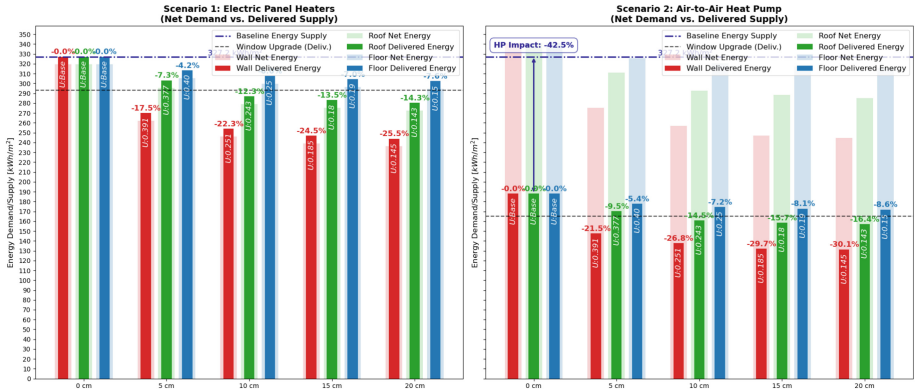


Fig. 3. Direct correlation between addition of different thickness of insulation in different building components with reduction of energy supply (Left: Without heat pump, right: With heat pump).

For an early 1900s conventional house, the most impactful single intervention is installing an air-to-air heat pump, which reduces supplied energy by 42.5%. Among envelope upgrades, wall insulation is the most effective, reducing supplied energy by 21.5% at 5 cm, 26.8% at 10 cm, and plateauing at 30% for 15 cm and 20 cm; these thicknesses correspond to net demand reductions of 17.5%, 22.3%, 24.5% and 25.5%, respectively. Roof insulation follows in effectiveness, offering supplied energy mitigation of 9.5% to 16.4% and net demand reductions of 7.4% to 14.3% across the 5 cm to 20 cm range. Floor insulation provides the least benefit for both energy supply and net demand mitigation (Fig. 3).

3.1.2 Energy Mitigation through a Combined Application of Thermal Insulation

Wall-roof insulation pairings outperform wall-floor configurations in reducing heating demand, as upward loss dominates and soil buffering limits floor insulation gains. With the heat pump, returns diminish beyond 10 cm wall +10 cm roof insulation, with further thickness yielding only marginal energy savings (Fig. 4).

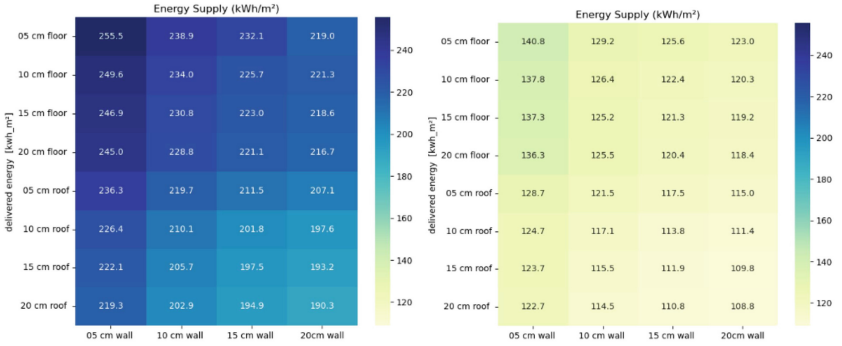


Fig. 4. Yearly energy supply (Left: Without heat pump, right: With heat pump).

3.1.3 CO_2 Emission Savings and Net-Zero Target by 2050

The heatmaps in Fig. 5 illustrate cumulative CO_2 emission reductions over the 60-year building lifetime for each insulation scenario, covering walls, floors, roof, and heat pump contributions. The results reveal diminishing returns with increasing insulation thickness: augmenting wall and roof insulation from 10 to 20 cm yields only a marginal improvement, from -49.16 to -51.11 kg CO_2 eq/m^2 with a heat pump, and from -27.40 to -32.03 kg CO_2 eq/m^2 without.

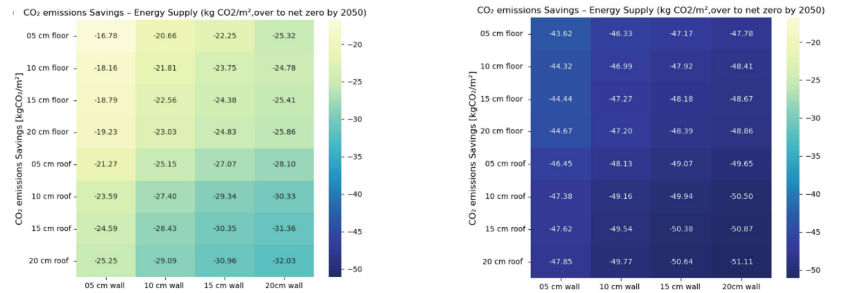


Fig. 5. CO_2 emission savings due to reduction in delivered energy to the building during operation (Left: Without heat pump, right: With heat pump).

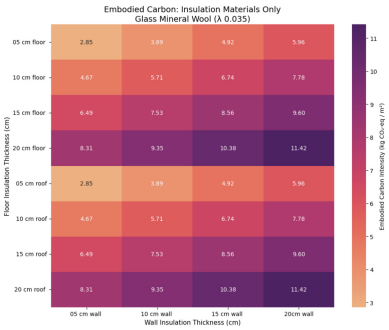


Fig. 6 Embodied carbon associated with thermal insulation materials exhibiting a thermal conductivity of 0.035 W/m·K [1].

3.1.4 Embodied CO_2 Emissions from Insulation and Heat Pump (Fig. 6)

3.1.5 Net Carbon Emission Savings

The insulation is assumed to require no replacement over the 60-year study period while the heat pump reference service life is assumed to be 15 years (Fig. 7).

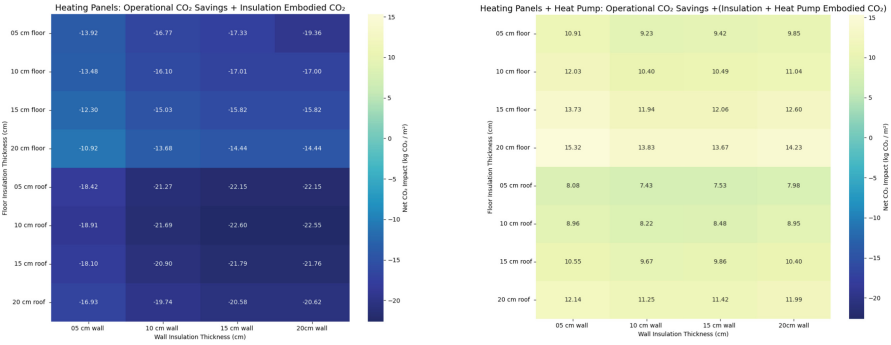


Fig. 7. Left: Operational CO_2-emission savings (without heat pump) plus embodied CO_2 from insulation. Right: Operational CO_2-emission savings (with heat pump) plus embodied CO2 from insulation and heat pump.

In this analysis, the results indicate that variations in insulation thickness combinations yield only marginal differences in net CO_2 savings across both scenarios. In the second scenario, which includes the integration of a heat pump, the net CO_2 emissions become positive across all configurations.

4 Discussion

The linear grid decarbonization trajectory defined by NS3720 represents a policy target rather than a guaranteed outcome. Occupant behavior introduces additional variability not captured in the simulation, as the well documented energy performance gap is particularly pronounced in older building stock. The assumed 15-year heat pump service life is likewise a conservative estimate; lifespan extension beyond 20 years under optimal maintenance would reduce replacement frequency and could shift the heat pump's net lifecycle CO_2 balance from a net increase to a net reduction. Finally, as the case study represents a single building derived from median dataset characteristics, results may not generalize to buildings with significantly different geometries or envelope to floor area ratios.

5 Conclusion

While a heat pump achieves the largest reduction in delivered energy (42.5%), its lifecycle CO_2 performance is compromised by embodied carbon from repeated replacements, yielding a net emissions increase across all insulation configurations over the 60-year period. Optimal insulation thicknesses range from 50 to 100 mm for the roof and 100 to 150 mm for walls. The most robust lifecycle CO_2 mitigation strategy therefore prioritizes moderate, typology-specific envelope upgrades. Heat pump integration remains contingent on substantial grid decarbonization and equipment service life exceeding current reference values before delivering a net carbon benefit.

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A Pilot Study of Environmental Variables and Air Quality During a Hot Mediterranean Summer. Projections on Physical Planning and Public Health

Tanya Saroglou[1], Hofit Itzhak-Ben-Shalom[2], Victor Multanen[1], Asaf Vanunu[3], Arnon Karnieli[3,4], David Katoshevski[1,4], Nadav Davidovitch[4,5], and Isaac A. Meir[1,4](✉)

[1] Department of Civil and Environmental Engineering, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Negev, Israel
sakis@bgu.ac.il

[2] The Porter School of the Environment and Earth Sciences, Department of Environmental Studies, Tel Aviv University, Tel Aviv, Israel

[3] Remote Sensing Laboratory, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Negev, Israel

[4] The Goldman Sonnenfeldt School of Sustainability and Climate Change, Ben-Gurion University of the Negev, Negev, Israel

[5] Faculty of Health Sciences, Ben Gurion University of the Negev, Negev, Israel

Abstract. This study investigates the relationship between urban environmental variables and air quality in the Mediterranean climate of Tel Aviv through in-situ monitoring of microclimatic conditions across three representative urban settings: two adjoining high-rise office towers, a pedestrian bridge located above a major urban highway and railway corridor, and a nearby low- to mid-rise residential neighborhood. Measurements of temperature, wind velocity and $PM_{2.5}$ concentrations were conducted during July under hot summer conditions. Data collected on site were compared with satellite observations and records from nearby meteorological and air-quality monitoring stations within a 5 km radius

Results reveal strong correlations between elevated pollutant concentrations, high air temperatures and reduced wind velocities. Urban morphology and building configuration significantly influence local microclimatic behavior, affecting pollutant dispersion and ventilation patterns. High-rise clusters can both enhance wind speeds locally through funneling effects and simultaneously create urban canyon conditions that trap pollutants

The findings highlight the critical role of urban form and building morphology in shaping air quality and thermal conditions. These insights emphasize the importance of integrating urban ventilation strategies and climate-responsive design principles into planning processes to mitigate urban heat island effects and reduce pollution exposure in dense cities

Keywords: Urban air-pollution · $PM_{2.5}$ · Urban ventilation · Monitoring · Tall buildings · Thermal comfort

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1 Introduction

Rapid urbanization and increasing population density have intensified environmental pressures within cities. Urban density alters local climate conditions, contributing to the formation of urban heat islands (UHI) and deteriorating air quality. These phenomena are closely associated with transportation activity, energy consumption and the urban morphology, affecting environmental variables and air quality [1].

Air pollution has become a major public health concern worldwide. Exposure to particulate matter, predominantly $PM_{2.5}$, is associated with respiratory and cardiovascular diseases and contributes to millions of premature deaths annually [2, 3]. The distribution and concentration of pollutants within cities are strongly influenced by microclimatic conditions such as wind velocity, temperature and urban geometry.

Tall buildings increasingly shape contemporary urban landscapes, especially in dense metropolitan areas. While high-rise development can limit urban sprawl, it also modifies airflow patterns, solar access and thermal conditions within the urban fabric [4]. Depending on their configuration, tall buildings can either improve ventilation through channeling effects or create canyons where pollutants accumulate. Tel Aviv provides a particularly relevant case study due to its rapid urban growth, dense urban morphology and hot Mediterranean climate. Previous research has documented significant urban heat island effects and microclimatic variations across the city [5].

However, there remains limited empirical research examining the interaction between urban form, environmental variables and air pollution at the micro-scale. This study aims to examine how different urban morphologies influence environmental conditions and pollutant concentrations. In-situ monitoring across three contrasting distinguished urban settings, investigate the relationships between temperature, wind velocity and $PM_{2.5}$ levels, providing insights to urban planning and public health.

2 Urban Study Area and Methods

2.1 Monitoring Sites

The study was conducted in Tel Aviv, Israel, located on the eastern Mediterranean coast. The city's climate is hot Mediterranean characterized by high summer temperatures, strong solar radiation and prevailing western sea breezes. The study was conducted during three days in July 2021 between 08:00 and 20:00, including two working days and one weekend day. July was selected because it represents one of the hottest periods of the year, allowing examination of environmental conditions under peak summer heat.

The three monitoring locations represent distinct urban morphologies and provide a useful comparison of microclimatic conditions within a dense urban environment, located within a radius of approximately 250 m:

1. **Yehudit Bridge** – a pedestrian crossing of Ayalon highway and railway.
2. **Alon Towers** – a 42-storey high-rise office complex of two towers.
3. **Bitzaron residential area** – a low- to mid-rise residential neighborhood.

All three monitoring sites are located in the eastern part of Tel Aviv, downwind of the dominant western wind, the Mediterranean breeze. Due to their position relative to the Ayalon highway and railway, it was assumed that pollution transported by the prevailing western winds could lead to higher pollutant concentrations there. It was also hypothesized that the high-rise tower cluster might generate a Venturi effect, influencing local airflow and pollutant dispersion.

Figure 1a presents the location of the three in-situ monitoring sites (green markers) together with six permanent meteorological and air-quality monitoring stations across the city (red markers). These stations are operated by the Ministry of Environmental Protection and the Ministry of Agriculture and Rural Development. Data from the permanent stations, located near the monitored sites, were used to validate the field measurements.

The HaShalom and HaHagana railway stations monitor air temperature, relative humidity and air quality. The Kremenetzky residential station records temperature and wind velocity, while the City Center station measures wind speed. The Lehi and Levinsky stations, both located in residential areas, monitor air quality. Figure 1 illustrates the location and characteristics of the three in-situ monitoring stations measuring air pollution concentrations and environmental variables such as air temperature, relative humidity, wind velocity and direction.



Fig. 1 a: Study area in Tel Aviv-Yaffo showing the six permanent meteorological stations (red) and the three in-situ monitoring sites (green). b: zoom-in of the monitoring locations representing different urban morphologies (Google Earth base map, [1]).

2.2 Data Collection

Air pollution was monitored using nitrogen oxide (NOx) and particulate matter ($PM_{2.5}$) sensors. Nitrogen oxides (NO and NO_2) were measured using a Monitor Labs ML 9841A NO–NO_2–NOx analyser (EU). Fine particulate matter concentrations ($PM_{2.5}$, $\mu g/m^3$) were recorded using a Continuous Ambient Particulate TEOM™ Monitor 1400ab (EU) and a Dylos PM1700 particle counter (USA). Data were collected continuously and stored in data loggers. Climatic variables were simultaneously monitored using HOBO USB Microstations (H-21). All instruments were calibrated, tested and compared under identical conditions prior to deployment. Two monitoring stations were installed at each study location to ensure cross-validation and calibration of the measurements. Table 1

shows the monitoring setup sites and monitoring equipment used for the collection of data.

Table 1. Location and characteristics of the three monitoring sites in Tel Aviv

Site	Alon Towers	Yehudit Bridge	Residency
Monitoring instruments	Two office towers connected by a pedestrian corridor, characterized by high pedestrian activity through the presence of restaurants and cafés.	A pedestrian and cyclist bridge crossing the Ayalon urban highway and railway corridor.	A residential balcony located along a narrow street in a neighborhood characterized by low-rise two-storey residential buildings.
			

3 Results

3.1 Air Temperature

Temperature measurements revealed significant differences between the three urban environments, for the three consecutive days investigated, see Fig. 2. The residential area consistently recorded the highest temperatures, reaching 33–36 °C, particularly during midday hours (13:00–16:00). In contrast, Yehudit Bridge and the Alon Towers exhibited lower temperatures, ranging between 28–32 °C. These lower values are likely related to the shading effects and improved airflow conditions created by the elevated structures and surrounding urban configuration.

Reduced traffic and rail inactivity on Saturday influenced the microclimate near Yehudit Bridge, resulting in temperature patterns like those observed at the HaShalom monitoring station**.** The Alon Towers initially recorded the lowest temperatures before gradually aligning with those at Yehudit Bridge later in the day. This trend suggests delayed heat absorption, likely associated with shading and enhanced airflow between the towers. Overall, the findings indicate that low-rise residential areas are more susceptible to heat accumulation, whereas a combination of low-rise and high-rise infrastructure can mitigate peak daytime temperatures, and shape local thermal conditions.

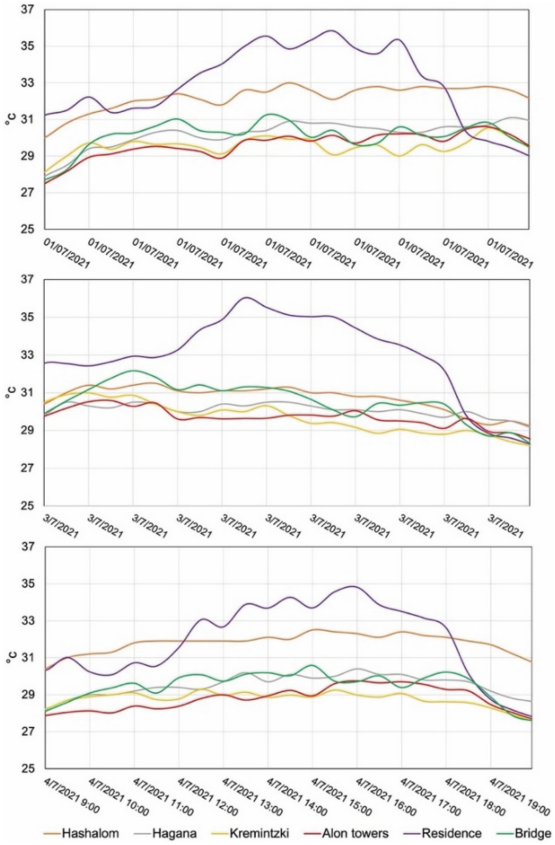


Fig. 2. Air temperature (°C) measured at the investigated sites between 08:00–20:00 during the monitoring campaign: (a) Thursday, 1 July 2021; (b) Saturday (weekend), 3 July 2021; and (c) Sunday (first workday of the week), 4 July 2021.

3.2 Wind Velocity

Overall, the wind velocity patterns highlight a strong relationship between urban configuration and wind circulation, see Fig. 3. The residential area consistently recorded the lowest wind speeds, ranging between 0.5–1.0 m/s, suggesting localized overheating. This phenomenon is likely related to the dense low-rise neighborhood configuration and its downwind position to the Alon Towers and surrounding high-rise development, which partially obstruct natural airflow. On Saturday higher wind velocities were observed at the Alon Towers, Kremenetzky, and City Center stations, likely due to their exposure to the prevailing Mediterranean breeze, while Yehudit Bridge remained relatively stagnant. Despite increased traffic activity on Sunday, no clear traffic-related influence on wind velocity was observed, indicating that urban morphology plays a stronger role in shaping airflow patterns than short-term human activity.

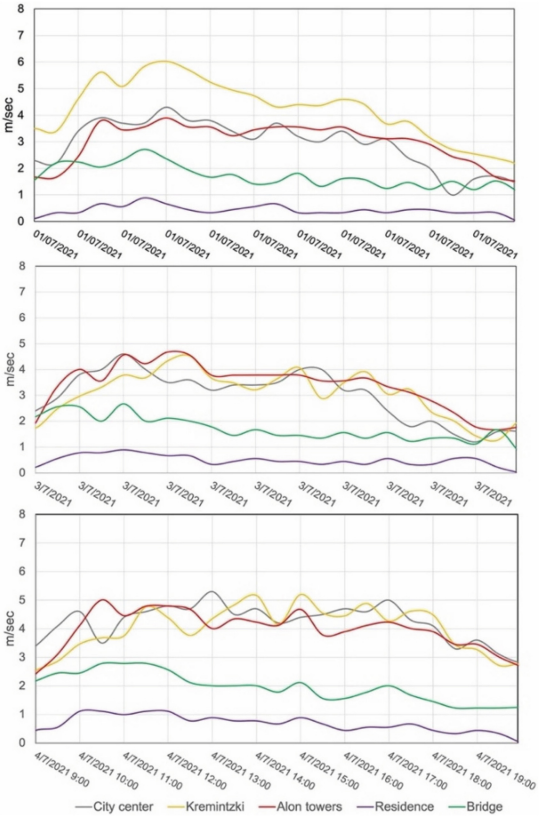


Fig. 3. Wind velocity (m/s) measured at the investigated sites between 08:00–20:00 during the monitoring campaign: (a) Thursday, 1 July 2021; (b) (weekend), 3 July 2021; and (c) Sunday (first workday of the week), 4 July 2021.

3.3 Air Pollution

In this section, air temperature and wind velocity are examined in relation to air pollution levels. Although all monitoring sites exhibited comparable temporal trends, the Alon Towers site demonstrated the clearest relationship between air temperature highs, wind velocity, and $PM_{2.5}$ concentrations, allowing the influence of meteorological conditions and urban morphology to be more clearly interpreted, see Fig. 4.

On Thursday, pollutant levels remained elevated during the morning hours before gradually declining as wind speeds increased. On Saturday (weekend), despite reduced traffic activity, $PM_{2.5}$ concentrations remained high throughout the day. Pollutant levels continued to rise even during periods of stronger winds (>6 m/s), suggesting that the high-rise canyon geometry may trap pollutants and limit effective dispersion. A similar pattern was observed at Yehudit Bridge, where $PM_{2.5}$ concentrations peaked at approximately 60–65 $\mu g/m^3$, likely influenced by regional haze, high temperatures, and limited atmospheric mixing during the heatwave. There is also the speculation that the absence

of train activity on Saturday passing beneath Yehudit Bridge and near Alon Towers could have reduced the piston dispersing effect that temporarily enhances pollutant dispersion during workdays when trains are running.

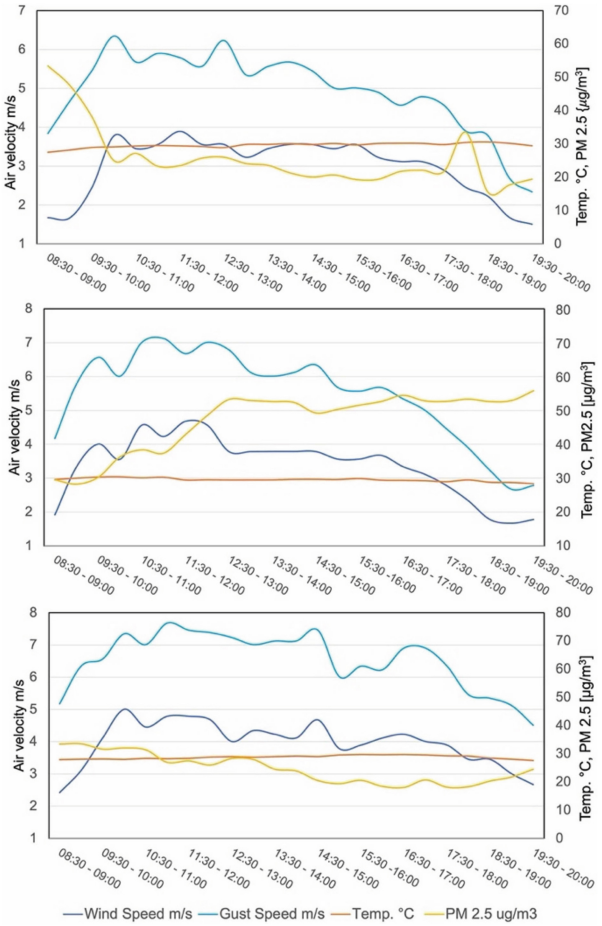


Fig. 4. Correlating PM2.5, Air Temperature (°C) and Air Speed (Wind and Gusts) in Alon Towers between 08:00–20:00 during the monitoring campaign: (a) Thursday, 1 July 2021; (b) Saturday, 3 July 2021; and (c) Sunday, 4 July 2021.

On Sunday (first workday of the week), concentrations decreased compared to Saturday at both sites, coinciding with slightly improved ventilation conditions and the resumption of urban activity. In contrast, the low wind speeds and limited air circulation throughout the three days at the residencial area, resulted in relatively stable but elevated $PM_{2.5}$ concentrations of around 30 µg/m^3. Overall, the results suggest that meteorological conditions, particularly during the heatwave, played a dominant role in pollutant accumulation**.**

4 Conclusions

This study examined the relationship between urban morphology, microclimatic conditions, and air pollution in Tel Aviv through in-situ monitoring at three representative urban typologies: Alon Towers, Yehudit Bridge, and low-rise residential area (Bitzaron). Results demonstrate a clear relationship between high $PM_{2.5}$ concentrations, elevated air temperatures, and low wind velocities, highlighting the role of urban form in local environmental conditions and pollution accumulation.

The residencial area exhibited the highest temperatures and lowest wind speeds, resulting in limited pollutant dispersion. In contrast, the high-rise cluster generated complex airflow patterns that enhanced ventilation but also created canyon effects capable of trapping pollutants. During the regional heatwave on Saturday, pollutant concentrations remained high despite reduced traffic activity.

These findings underline the importance of climate-sensitive urban planning, particularly in rapidly densifying Mediterranean cities. Ensuring adequate ventilation corridors, appropriate building spacing, and the integration of green spaces can improve urban airflow and reduce both heat accumulation and pollutant exposure as climate change intensifies heatwaves and urban air-quality challenges.

Acknowledgments. This research is partly supported by the Center for Energy and Sustainability, Ben-Gurion University of the Negev.

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A Pilot Case in Sustainable Renovation of Modern Cultural Heritage

Elias V. Messinas[1](✉) and Tanya Saroglou[2]

[1] Faculty of Design, Holon Institute of Technology, Holon, Israel
messinase@hit.ac.il
[2] Department of Civil Engineering and Environmental Engineering, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Negev, Israel

Abstract. Achieving sustainable renovation in historic buildings requires reconciling two often competing goals: reducing operational and embodied carbon while safeguarding architectural identity and cultural value. As the European Union advances its 2050 net-zero objectives, the need for renovation strategies that integrate regulatory, technical, and heritage-conservation perspectives has become central to policy and practice. The Horizon Europe project SINCERE responds to this challenge by developing adaptive, resource-efficient renovation pathways for modern-period heritage, combining low-carbon materials, renewable energy technologies, and digital decision-support tools. This paper presents the SINCERE pilot at Building 3 of the Holon Institute of Technology, a 1972 Brutalist reinforced-concrete structure later modified through roof extensions and accessibility upgrades. The project explores how sustainable design strategies—thermal insulating mortars, radiative cooling coatings, and building-integrated photovoltaics—can be incorporated into an existing cultural-heritage fabric without compromising authenticity. The methodological framework employs HBIM and digital-twin environments to simulate energy performance, assess climatic responsiveness, support maintenance planning, and evaluate results towards long-term carbon reduction. Beyond technical validation, the pilot functions as an educational and participatory platform: students and faculty engage in material testing, installation monitoring, and performance interpretation alongside SINCERE partners. Concluding, the study demonstrates how digital workflows, climate-adaptive materials, and nature-based cooling strategies can be integrated into the renovation of modern heritage buildings, offering transferable insights for stakeholders seeking resilient, low-carbon, and culturally responsible reuse of existing building stock

Keywords: Cultural Heritage · Net-Zero · Brutalist · Architecture · Energy Performance

1 Introduction

The renovation of cultural heritage buildings lies at the intersection of conservation, environmental performance, and contemporary use. Buildings account for approximately **40% of energy consumption in the European Union**, making the built environment

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a key sector in achieving climate neutrality targets [3]. While much attention has been directed toward new construction, the renovation of heritage buildings—especially those from the modernist period—remains under-addressed.

Modern heritage buildings constructed between the mid-20th century and the 1970s frequently lack insulation and rely on outdated mechanical systems. Retrofitting them is technically challenging because interventions must respect architectural integrity and historic significance. International organizations such as ICOMOS emphasize the need for integrated approaches that combine climate action with cultural heritage preservation [8].

The **Horizon Europe SINCERE project** responds to this challenge by developing adaptive renovation methodologies for post-war modern architecture. The project tests innovative materials, energy-generation technologies, and digital monitoring systems across several pilot sites. This paper focuses on the HIT Building 3 pilot in Holon, Israel, examining how sustainable renovation strategies can be applied to a Brutalist structure while preserving its architectural identity.

2 Cultural Heritage Buildings

2.1 Sustainable Renovation of CH Buildings

Sustainable renovation has become a central theme in architectural and conservation discourse. Traditional conservation approaches emphasized preserving original materials and forms, whereas contemporary strategies increasingly support adaptive reuse and energy-efficient retrofits [5].

Adaptive reuse extends the lifecycle of buildings and reduces embodied carbon while maintaining cultural continuity [2]. However, renovation interventions must reconcile energy performance with conservation constraints. Guidelines from ICOMOS and Historic England advocate minimal and reversible interventions that preserve architectural authenticity [9].

Recent European directives, including the **Energy Performance of Buildings Directive (EPBD)**, promote performance-based renovation strategies that consider lifecycle emissions and compatibility with historic fabric. Sustainable renovation therefore requires a holistic approach incorporating passive design strategies, compatible materials, and digital tools.

Material selection plays an important role in heritage renovation. Breathable insulation materials, lime-based mortars, and natural materials help maintain hygrothermal balance and protect historic structures [1]. Passive strategies such as natural ventilation, shading, and thermal inertia can further improve indoor comfort without compromising architectural integrity.

Digital technologies increasingly support renovation decision-making. Tools such as **Historic Building Information Modelling (H-BIM)** and IoT-based monitoring systems enable simulation, predictive maintenance, and performance tracking. These technologies allow architects, engineers, and building managers to develop interventions that are both environmentally efficient and culturally sensitive.

2.2 Modern and Brutalist Heritage

Modernist and Brutalist buildings occupy a contested position within heritage discourse. Characterized by exposed concrete surfaces and monumental forms, Brutalist architecture is often controversial [7] but represents an important architectural legacy of the post-war period [10].

Many modern heritage buildings face demolition or neglect because they are not widely recognized as heritage assets. Although iconic works by architects such as **Le Corbusier, Louis Kahn, and Marcel Breuer** receive protection, numerous institutional and civic buildings from the same period remain vulnerable.

In Israel, modernist and Brutalist architecture forms an integral part of the country's architectural identity. Many institutional buildings constructed after 1948 independence reflect ideals of progress and civic identity. However, these buildings often suffer from energy inefficiency and limited recognition within heritage protection frameworks (Fig. 1).

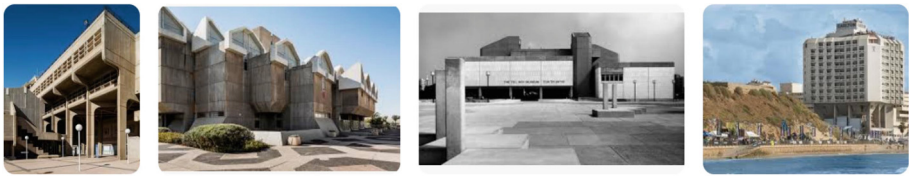


Fig. 1. Examples of Brutalist architecture in Israel (left to right): Ben Gurion University; Tel Aviv Museum of Art; Carlton Hotel Tel Aviv (Google search accessed March 5, 2026)

3 The SINCERE Project

3.1 General

The **SINCERE project** addresses the sustainable renovation of modern heritage buildings through interdisciplinary collaboration. The project combines conservation principles with energy transition goals by testing innovative technologies across several pilot sites.

Key components of the SINCERE methodology include: interdisciplinary collaboration among architects, engineers, and conservation specialists; performance-based evaluation of energy and environmental performance; digital tools such as H-BIM and Digital Twin platforms; testing of innovative materials compatible with historic buildings (Fig. 2).

3.2 Innovative Materials

Historic buildings often cannot accommodate conventional insulation solutions. The application of new materials therefore plays a crucial role in improving energy performance while maintaining architectural authenticity. Among the technologies tested in

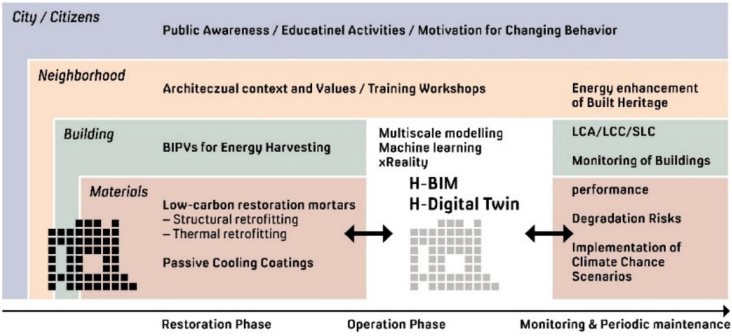


Fig. 2. SINCERE: Different scales and actions towards net-zero energy buildings (SINCERE)

SINCERE are sustainable, and cost-effective restoration materials and practices, energy harvesting technologies, ICT tools and socially innovative approaches, applied on the building structure and external envelope - opaque and transparent.

These technologies enable energy efficiency through enhancement of the building envelope combined with renewable energy technologies, while minimizing visual impact on historic buildings.

3.3 The HIT Pilot Case Study

The SINCERE project includes four pilot sites that allow evaluation of climate-specific renovation strategies and architectural contexts: 1. **Algete, Spain** – testing facility; 2. **Rhodes, Greece** – neoclassical school building; 3. **Holon, Israel** – Brutalist academic building; 4. **Ostrava, Czechia** – industrial heritage complex (Fig. 3).



Fig. 3. SINCERE four pilot sites representing buildings of the 20th century cultural heritage, of diverse uses, different scales and climatic zones (from left to right): Algete, Rhodes, Holon, and Ostrava (SINCERE)

Pilot 3 is the Holon Institute of Technology building 3, an academic building situated in a semi-arid coastal zone. The case study is managed by SINCERE partner ECOAMA. Constructed in 1972 in the Brutalist style, it is characterized by exposed reinforced concrete and deep shading elements. The building has undergone several modifications including a new light metal roof addition and accessibility upgrades. Energy performance is characterized by high cooling demand during hot summers (Fig. 4).

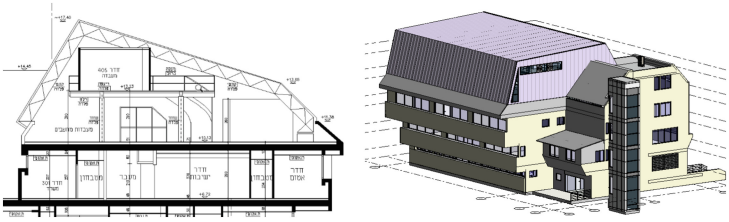


Fig. 4. Section (left) and BIM model by ECOAMA (right) of the gallery space under the roof of the SINCERE Pilot Building 3, at Holon Institute of Technology, Holon, Israel (SINCERE)

3.4 Energy Performance Challenges

The building exhibits significant energy inefficiencies. Uninsulated concrete walls and lightweight metal roof have thermal transmittance values ranging from 3.14 to 3.51 W/m^{2}K, while the roof reaches 5.25 W/m^{2}K, far exceeding those permitted by contemporary Israeli green building standard 5282: 0.60 W/m^{2}K for walls and 1.50 W/m^{2}K for roofs. Resulting in high mechanical cooling demand during hot summers.

Holon's climate zone enables the SINCERE project to monitor the behavior of the proposed intervention in a Mediterranean climate with hot, dry summers and mild, wet winters, with average temperatures at 25 °C and average humidity at 72.5%, with transitional influences from the surrounding desert areas. Due to the high temperatures, the unassisted comfort zone in the psychrometric chart is only 6%, with 94% passive and active (mechanical) solutions needed for thermal comfort (Fig. 5).

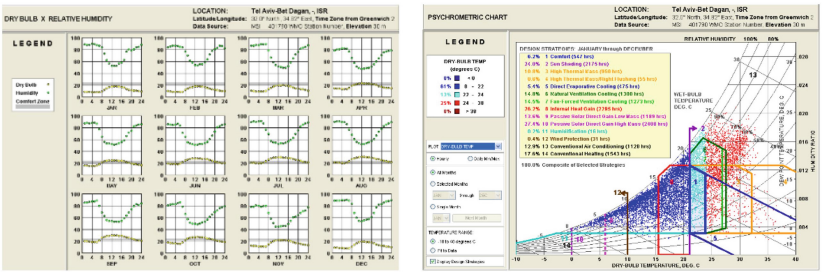


Fig. 5. (left) Annual dry bulb temperatures and humidity (left) in the Holon area and (right) psychrometric chart by Climate Consultant (SINCERE)

HIT's uninsulated wall and roof envelope contributed to thermal bridging and excessive heat gain, while its aging mechanical systems further exacerbated operational inefficiencies. As a result of the increased temperatures within the premises, and the discomfort and increasing rate of illness reported by the users, in 2022 the administration considered insulating the roof or installing additional air-conditioning units. Due to cost and construction constraints, it decided to purchase 4 AC units type 65 WIND by Tadiran, with consumed power in cooling 5.230 KW, estimated at 36.61 KWh daily each, a total estimated additional electric load for the building of 146.5 KWh daily. The provided

immediate thermal comfort, but increased energy consumption. In addition, the external units were exposed on the edge of the roof, while the channels where built-in with sheetrock in suspended ceilings.

This solution introduced new energy burdens: the building, which already consumed approximately 33% more than benchmarks for governmental office buildings, saw an additional 6% increase in energy use from the new AC units alone - based on technical calculations in the absence of historical metered data. Notably, a comparative analysis showed that had the administration opted for roof insulation instead, the return on investment (ROI) would have been approximately 11.1 years, not accounting for the additional cost for mechanical cooling in peak summer months. The challenges faced by the Holon building, reflect similar dilemas by modern cultural heritage, and thus assigned it as an applicable pilot for the SINCERE project.

3.5 Holon Pilot Interventions

Within SINCERE, three main interventions are being tested at the Holon pilot: **Thermal insulating mortars** using hempcrete, a bio-based low-density composite, and PCMs (Phase Change Materials), capable of storing and releasing thermal energy through phase transitions - materials that improve thermal performance while preserving and enhancing concrete surfaces; **Radiative cooling coatings** - surface treatments reduce solar heat gain without altering the building's appearance; **Building-integrated perovskite solar cells (BIPVs)** - photovoltaic cells integrated into glazing elements generate renewable energy while maintaining architectural transparency (Fig. 6).

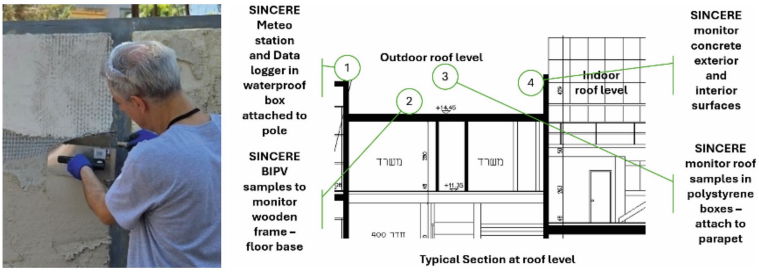


Fig. 6. (left): Applying thermal insulating mortars during the advanced workshop on innovative mortars for structural and thermal retrofitting organized by NCSR Demokritos in Athens, Greece, and (right) diagram of the SINCERE interventions at the Holon pilot (SINCERE).

Monitoring the interventions using embedded sensors collects data on thermal conductivity, surface temperature, material degradation over time. and energy performance. They are further evaluated using H-BIM and Digital Twin systems as part of the SINCERE program (Fig. 7).

3.6 Integration with Academic Use

The HIT academic campus enables integration of the pilot into research and education. Students participate in workshops, data collection, and monitoring activities,



Fig. 7. (left): Snapshots of the mobile screen of the SINCERE digital app of the BIM-based mobile application by Up2Metric that exploits Mixed Reality (MR); (right) snapshot of the SINCERE Virtual Reality (VR) application by Nurogames, for the Holon pilot (SINCERE)

transforming the building into a living laboratory for sustainable heritage renovation (Fig. 8).



Fig. 8. (left) Design workshop of HIT with Democritus University of Thrace (DUTH) in Greece, to explore the reuse of materials of industrial heritage; (right) exploring in short videos the 'Talking Buildings' tool developed by Nethood in SINCERE (E. Messinas & SINCERE)

Educational workshops organized by HIT within the SINCERE framework have involved universities from Greece and Cyprus, fostering interdisciplinary collaboration and knowledge exchange. Similarly within the HIT campus, the SINCERE pilot enables seamless integration of the project's goals into its curriculum, allowing active participation of students in the process, turning the pilot into a living laboratory for sustainable design in innovation for cultural heritage. The building becomes not only a site for architectural preservation and energy performance optimization, but also an inspirational platform for student-led experimentation and innovation.

4 Conclusion

The HIT pilot highlights both the potential and complexity of sustainable renovation in modern heritage buildings. The renovation of HIT Building 3 demonstrates how modern heritage buildings can be adapted to meet contemporary environmental goals while preserving their architectural character. Through the integration of advanced materials, digital monitoring technologies, and academic collaboration, the SINCERE project provides a replicable model for sustainable renovation of cultural heritage buildings in general and Brutalist architecture in particular.

The case also illustrates the importance of policy frameworks supporting the renovation of post-war architecture, which is often excluded from heritage protection policy, thus encourage preservation with compatible energy performance improvements.

As climate targets approach for **2030 and 2050**, the renovation of post-war heritage buildings will become increasingly important. The methodologies tested in SINCERE contribute to developing strategies that reconcile energy efficiency, cultural heritage preservation, and sustainable urban development.

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LCA-Based Method for Sustainable Concrete Mix Design in Uruguay

P. Codina(✉), J. Cabrera, P. Vila, and M. N. Pereyra

Universidad de la República, Montevideo, Uruguay
pcodina@fing.edu.uy

Abstract. This study presents the application of a life cycle assessment (LCA)-based calculation method to support sustainable concrete mix design in Uruguay. The aim was to evaluate the environmental performance of traditional and alternative concrete mixtures with comparable technical performance, representative of ready-mix concrete production in Uruguay. The functional unit was 1 m^3 of concrete. Three types of concrete were analyzed: conventional concrete (CC) with two strength levels (25 MPa and 40 MPa) and a self-compacting concrete (SCC). For each case, reference mixtures produced with Portland cement were compared with alternative mixtures incorporating supplementary materials. In CC mixtures, calcined clay (metakaolin) was used as a partial replacement of Portland cement, while in SCC mixtures the cement was partially replaced by quarry crushing fillers obtained from granodiorite and limestone stone powder. The LCA system boundaries were defined as cradle-to-construction site (A1-A4) according to UNIT-ISO 21930, including raw material production, transport to the batching plant, concrete production, and delivery to the construction site. Life cycle inventory data were mainly obtained from the Ecoinvent v3.x database and complemented with local information. Environmental impacts were evaluated using the ReCiPe 2016 Midpoint method, considering the impact categories defined within this method. The results indicate that reducing Portland cement content through the use of calcined clay and quarry fillers significantly decreases environmental impacts, particularly in climate change and fossil resource scarcity, while maintaining the required technical performance

Keywords: Life Cycle Assessment · Concrete Mixtures · Calcined Clay · Crushed Rock Powder · Environmental Impact

1 Introduction

The construction sector produces significant environmental impacts due to the intensive consumption of raw materials and energy required to produce construction materials and infrastructure, as well as the associated greenhouse gas (GHG) emissions generated during industrial processes such as cement production. Globally, the building and construction sector accounts for a substantial share of environmental burdens, including around 30–40% of global energy consumption and up to 39% of energy-related CO_2 emissions [1, 2]. In addition, cement production alone is responsible for approximately 5–8% of

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global anthropogenic CO_2 emissions, making it one of the most carbon-intensive industrial activities [3–6]. The construction sector is also associated with other environmental impacts such as air pollution, resource depletion and emissions affecting ecosystems [7, 8].

In Uruguay, these impacts are reflected in the National Greenhouse Gas Inventory (INGEI). According to the latest reported data for 2022, the Industrial Processes and Product Use (IPPU) sector emitted 907 kt CO_{2eq} [9]. When emissions derived from energy consumption in industrial activities reported under the Energy sector of the national inventory are also considered, the overall contribution of industrial activities represents approximately 6.8% of the total national GHG emissions. Carbon dioxide is the predominant gas in the IPPU sector, representing around 55% of its emissions. Within this sector, Portland cement production constitutes the main emission source, accounting for about 83% of CO_2 emissions and approximately 46% of the total emissions of the IPPU sector. Considering the central role of cement as the primary binder in concrete, these results highlight the environmental relevance of evaluating concrete production through life cycle assessment approaches and exploring alternative materials capable of reducing clinker consumption in concrete mixtures.

The aim of this study was to assess selected environmental impact categories associated with the production of concrete mixtures developed within ANII project "*Concrete design using non-traditional materials available in Uruguay with a performance-based and sustainable approach*", through a life cycle assessment approach. The study considered both conventional concrete (CC) and self-compacting concrete (SCC) incorporating alternative materials such as calcined clay and crushed rock powders. The reference mixtures correspond to concretes commonly used in the Uruguayan construction sector, while the alternative mixtures incorporate supplementary materials aimed at reducing clinker content. The assessment aimed to compare the environmental performance of these mixtures while maintaining comparable mechanical performance. The life cycle assessment was conducted in accordance with the methodology defined in UNIT-ISO 14040 [10] and UNIT-ISO 14044 [11]. The system boundaries were defined according to UNIT-ISO 21930 [12], modules A1-A4, which include raw material extraction and production, transportation of materials to the concrete batching plant, concrete production, and the delivery of ready-mix concrete to the construction site.

2 Materials and Methods

2.1 Materials

Portland limestone cement (CPF40) and ordinary Portland cement (CPN40), both in accordance with UNIT 20 [13], were used in concrete mixtures. CC mixtures incorporated CPF40 together with a naphthalene-based water-reducing admixture, whereas SCC mixtures were produced using CPN40 and a polycarboxylate-based high-range water-reducing admixture.

Three supplementary materials (SCMs) were used. Calcined clay (metakaolin), used as a supplementary cementitious material in CC mixtures, was obtained from central Uruguay, specifically from the locality of El Cordobés (Cerro Largo). In SCC mixtures, two crushed rock powders were incorporated as mineral fillers: granodiorite powder

(FG), sourced from Cruz de Carrasco (Montevideo) and limestone powder (FC), obtained from a quarry near Nueva Carrara (Maldonado).

Two natural sands of fluvial origin from the Santa Lucía River were used: a coarse sand (AGPP) and a fine sand (AFT). Coarse aggregates included crushed stone (CM) from a quarry in Cruz de Carrasco (Montevideo) and natural gravel (PR) from Las Piedras (Montevideo).

For CC mixtures, two strength levels were evaluated, corresponding to PR25 and CM40. For each level, a reference mixture and an alternative mixture with partial replacement of cement by calcined clay (PRC1 and CMC1, respectively) were considered. For SCC, one reference mixture (SCCN) and two alternative mixtures with quarry powders as fillers (SCCFG and SCCFC) were analyzed, as summarized in Table 1.

Table 1. Composition (kg/m^3) and properties of CC and SCC mixtures.

Mix ID	Fc[(1)] (MPa)	Slump (cm)	Cement (kg)	SCMs (kg)	Coarse aggregate (kg)	Sand[(11)] (kg)	Water (l)	Admixture (kg)
PR25-Ref	28.9	7.5	320.0[(3)]	0.0	966.0[(8)]	790.0	195	0.00
PRC1	30.8	5.0	224.0[(3)]	85.4[(5)]	966.0[(8)]	790.0	195	0.00
CM40-Ref	47.7	20.0	470.0[(3)]	0.0	891.0[(9)]	732.0	200	2.82[(12)]
CMC1	43.9	16.0	329.0[(3)]	125.5[(5)]	891.0[(9)]	732.0	200	3.29[(12)]
SCCN-Ref	60.7	70.5[(2)]	628,9[(4)]	0.0	781.6[(10)]	708.1	215	7.55[(13)]
SCCFG	36.8	76.0[(2)]	413.7[(4)]	177.3[(6)]	781.6[(10)]	708.1	218	3.31[(13)]
SCCFC	50.5	76.5[(2)]	453.4[(4)]	194.3[(7)]	781.6[(10)]	708.1	198	4.53[(13)]

[(1)]: average compressive strength at 28 days; [(2)]: Slump flow; [(3)]: CPF40; [(4)]: CPN40; [(5)]: Calcined Clay; [(6)]: FG; [(7)]: FC; [(8)]: PR; [(9)]: CM5/20; [(10)]: CM5/14; [(11)]: AGPP+AFT; [(12)]: Sikament 290N; [(13)]: ViscoCrete 6.

2.2 Goal and Scope Definition and System Boundaries

The goal of the LCA was to compare the environmental performance of selected concrete mixtures with equivalent functional performance. The assessment was conducted following a cradle-to-construction site approach (modules A1-A4), in accordance with UNIT-ISO 21930 [12]. These stages include raw material extraction and production (A1), transportation of materials to the concrete batching plant (A2), concrete production (A3), and the transport of ready-mix concrete from the batching plant to the construction site (A4). The placement and finishing of concrete in the structural element (module A5) were not included within the system boundaries of this study.

Module A4 only accounts for the environmental impacts associated with the transportation of ready-mix concrete from the concrete batching plant to the construction site. The modelling approach assumes a central mix configuration, in which concrete is fully mixed in a stationary plant mixer prior to loading into delivery trucks; therefore, the mixing process is entirely included in module A3. However, under typical conditions in Uruguay, concrete production is predominantly based on truck-mixing operations, where

mixing occurs within the truck mixer after loading and is completed at the construction site. This difference was a modelling simplification adopted.

2.3 LCA Modelling Assumptions and Inventory Data

The life cycle assessment model was developed in SimaPro Craft (version 10.3.0.1) using data obtained from the experimental mix designs and complemented with secondary data from the Ecoinvent v3.x database [14]. Assumptions regarding transportation distances, electricity consumption and production processes were defined to represent the concrete production conditions in the Montevideo Metropolitan Area.

The functional unit was defined as 1 m^3 of concrete produced at the batching plant. The transport distances considered in the LCA model were as follows: 385 km for CPN40, 107 km for CPF40, 246 km for the calcined clay, 30 km for the gravel, 14 km for the crushed stone, 45 km for AFT, 67 km for AGPP, 14 km for FG, and 102 km for FC. Additionally, 7.5 km between the concrete batching plant and the construction site was considered. Regarding transport modelling, cement and calcined clay were modelled using heavy-duty trucks (32 metric ton, diesel, EURO 3), while aggregates (sand and coarse aggregates), the crushed rock powders (FG and FC) and transport of ready-mix concrete were modelled using medium-duty trucks (7.5–16 metric ton, diesel, EURO 3), in accordance with the datasets available in the database.

The location of the ready-mix concrete plant was defined hypothetically as the barycenter of the three main ready-mix plants in the metropolitan area of Montevideo, assuming a representative peripheral location. The construction site was similarly defined as a hypothetical point at the geographical center of the city.

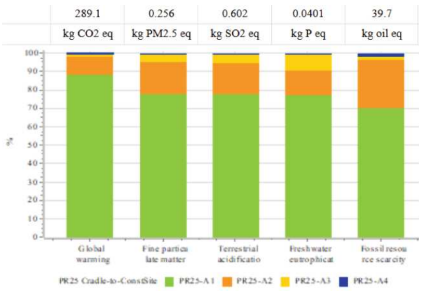
2.4 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) was carried out using the ReCiPe 2016 Midpoint method available in SimaPro. Table 2 summarizes the relationship between these general impact categories and the corresponding ReCiPe 2016 Midpoint indicators considered in the study.

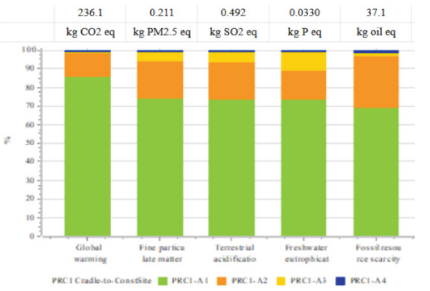
Table 2. General impact categories and ReCiPe 2016 Midpoint indicators.

General Impact category	ReCiPe 2016 Midpoint indicators used in SimaPro
Climate Change	Global warming (GWP)
Human health	Fine particulate matter formation (FP)
Ecosystem quality	Terrestrial acidification (TA) and Fresh water eutrophication (FWE)
Non-renewable resource use	Fossil resource scarcity (FRS)

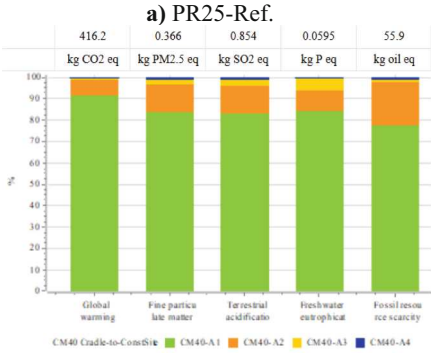
3 Results and Discussion



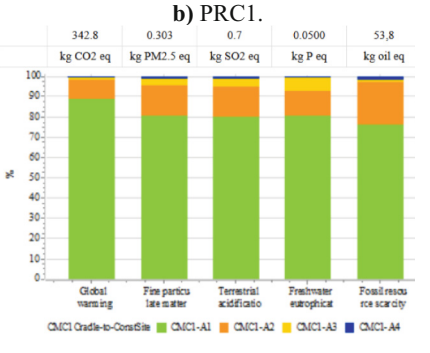
a) PR25-Ref.



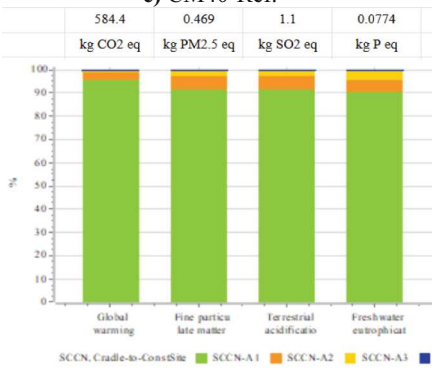
b) PRC1.



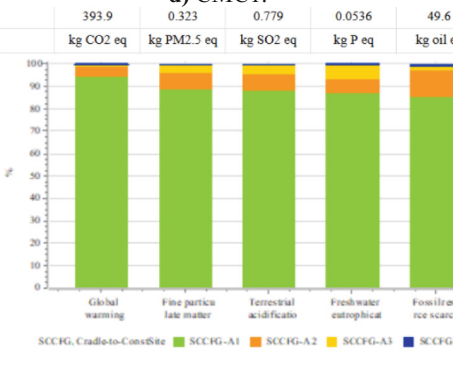
c) CM40-Ref.



d) CMC1.

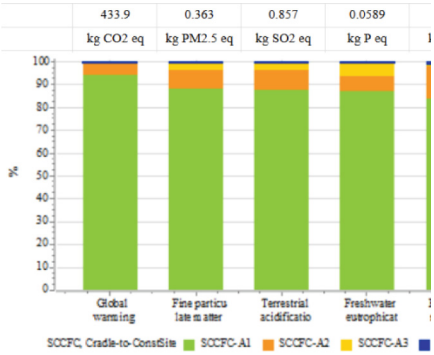


e) SCCN-Ref.

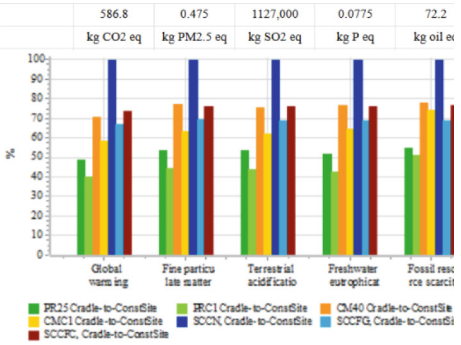


f) SCC-FG.

Fig. 1. Relative contribution of each life cycle stage to the selected environmental impact categories and comparison among different concrete mixtures.



g) SCC-FC.



h) environmental impact categories for CC and SCC mixtures.

Fig. 1. (*continued*)

Figure 1 a–g present the contribution of the different life cycle modules (A1-A4) to the environmental impacts of the analyzed concrete mixtures. For each mixture, the stacked bars represent the relative contribution of each life cycle module within the cradle-to-construction site system boundary, allowing the identification of the processes that dominate the environmental profile of each concrete. The total impact value for each category is shown above the corresponding bars. Figure 1h shows the comparative environmental impact categories for CC and SCC mixtures. The values are expressed as percentages relative to the mixture with the highest impact in each category.

PR25 presents the lowest environmental impacts due to its lower cement content, whereas CM40 shows higher impacts associated with increased binder demand. SCCN exhibits a distinct profile due to its higher paste content and the use of chemical admixtures for self-compatibility.

Although the transport stages included in modules A2 and A4 contributed to the overall impacts, their relative contribution was significantly lower than that associated with raw material production in module A1, particularly cement manufacture. These results highlight that, within the cradle-to-site boundary, the environmental performance of ready-mix concrete was largely governed by the cement content and paste volume of the mixture. When considering the Global Warming Potential (GWP) indicator, the upstream production of raw materials (A1) represented the largest contribution for all the evaluated mixtures, accounting for approximately 88% of total emissions for PR25, 91% for CM40, and up to 96% for SCCN. Transportation of materials to the concrete plant (A2) represented the second most significant contribution, ranging from about 3% to 11% depending on the mixture, while the concrete manufacturing stage (A3) and the transport of ready-mixed concrete to the construction site (A4) represented only minor shares of the total GWP.

The comparison between mixtures PR25 and CM40 and their corresponding mixtures incorporating calcined clay (PRC1 and CMC1) highlights the influence of partially replacing Portland cement with calcined clay. The results showed that the mixtures containing calcined clay showed lower environmental impacts in most of the evaluated midpoint categories, particularly in GWP and fossil resource scarcity (FRS), due to the

reduction in cement consumption. In terms of GWP, the incorporation of calcined clay resulted in a reduction of approximately 18% compared with the respective reference mixtures (PR25 and CM40). This behavior was consistent with previous life cycle assessment studies of concrete, which identify cement production as the main contributor to environmental impacts [15].

The comparison between the self-compacting concrete mixtures SCCN, SCCFG, and SCCFC highlights the influence of incorporating quarry powders on the environmental performance of the mixtures. The results indicated that both SCCFG and SCCFC exhibited lower environmental impacts than the reference SCCN mixture across all the evaluated categories. In terms of GWP, SCCFG showed a reduction of approximately 33%, while SCCFC achieved a reduction of about 26% relative to SCCN. These improvements were primarily attributed to the lower cement content and, in the case of SCCFG, the shorter transport distance between the quarry and the concrete batching plant.

4 Conclusions

This study applied an LCA-based approach to evaluate the environmental performance of conventional and self-compacting concrete mixtures incorporating locally available supplementary materials in Uruguay. The results showed that environmental impacts were mainly governed by raw material production, particularly Portland cement manufacture, which dominated module A1 in all mixtures.

In conventional concrete, the partial replacement of Portland cement with calcined clay reduced the GWP by approximately 18% compared with the reference mixtures. In self-compacting concrete, the use of crushed rock powders as mineral fillers led to GWP reductions of approximately 33% for SCCFG and 26% for SCCFC relative to the reference SCC mixture, mainly due to lower cement content and, for SCCFG, the shorter transport distance of the filler.

A reduction in fine particulate matter formation was also observed in mixtures with lower clinker content, suggesting additional benefits for human health. Overall, the results indicate that clinker reduction strategies, combined with locally available supplementary materials, can improve the environmental performance of concrete mixtures in Uruguay while maintaining suitable functional performance.

However, the results should be interpreted within the cradle-to-construction site boundary considered in this study, and future work should include sensitivity and uncertainty analyses, as well as a broader assessment of additional life cycle stages.

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Building Green Campuses: A Framework for Sustainable Higher Education

Rame Likaj, Gezim Hoxha(✉), Bukurije Hoxha, Blerina Blykbashi, Eronita Jasiqi, Erion Shala, and Liridon Bytyçi

Faculty of Mechanical Engineering, University of Prishtina, 10000 Prishtina, Kosovo
gezim.hoxha@uni-pr.edu

Abstract. Conducted within the Kosovo–Albania bilateral project "Education and Energy Management on University Campuses", this study combines a survey of 232 respondents across 14 academic units with carbon footprint analysis to assess energy use, resource consumption, mobility and sustainability practices. The results show that energy consumption is primarily concentrated in laboratories, IT systems, cooling and lighting, reflecting the structural requirements of engineering education and the infrastructure dependent nature of university energy use. While environmental awareness and individual engagement in sustainable practices are relatively high, institutional systems for energy management, resource efficiency and sustainability integration remain limited. In the carbon-intensive energy in Kosovo context, even modest efficiency improvements can contribute meaningfully to emission reduction, while digitalization introduces both efficiency gains and increased ICT-related energy demand. The findings indicate that sustainability outcomes are primarily determined by institutional and infrastructural conditions rather than individual behaviour, underscoring the need for governance-driven rather than behaviour-focused interventions. The study is relevant for universities in transitional contexts seeking to improve environmental performance under constrained governance and infrastructure systems.

Keywords: Carbon footprint · Energy saving · Eco-friendly transport · Recyclable materials · Sustainable campus

1 Introduction

Universities play an important role in shaping knowledge, skills and attitudes for sustainable development. This study, part of a bilateral collaboration between FME - University of Prishtina and FE - University of Tirana, examined sustainability practices and perceptions within the university community to inform a draft Green Campus framework aimed at integrating environmental sustainability into academic life, research and institutional culture while improving educational and energy management capacities [1].

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2 Literature Review

National studies and policies in Kosovo and Albania address climate change and co_2 emissions. However, there is a lack of studies identifying specific sources, reasons, and approaches for lowering emissions in schools and higher education institutions [2, 3]. Some energy audits and efficiency improvements have been completed, but surveys show that professors and students are still dissatisfied with the incorporation of environmental sustainability into courses and university operations remain insufficiently sustainable [4]. Recycling, reuse, and reduction efforts on campuses are scarce, and environmental awareness programs are often infrequent [5]. This emphasizes the need to increase understanding among all educational stakeholders about sustainability, emission sources, environmental damage, and energy-saving methods.

In contrast, the EU and the United States have produced extensive guidelines, tools, and best practices for educational institutions to reduce emissions and promote renewable energy [6–8]. These frameworks emphasize active engagement of staff and students while providing pathways to carbon neutrality and greenhouse gas reduction goals [9, 10]. Educational institutions should also be categorized by type, structure, practices, energy sources, and climate zone to allow for realistic comparisons, as evidenced by 29 existing categorisation standards [11]. According to studies, universities are among the greatest energy consumers in the public sector, second only to hospitals in terms of carbon intensity [12].

Energy conservation reduces overall consumption through behavioral or operational adjustments, whereas energy efficiency achieves similar outcomes through technological improvements [13, 14]. Linking energy education to institutional policies can increase the effectiveness of sustainability-oriented action [15]. Educational institution initiatives, such as lectures, training, fairs, and contests, encourage students and staff to use energy responsibly while also supporting larger sustainability goals [16]. Context-specific interventions, including low-emission vehicles, emission testing, and remote health monitoring, have been shown to reduce co_2 emissions and improve public health [17].

3 Methodology

This study adopts a mixed-methods framework within the Kosovo–Albania project "Education and Energy Management in University Campuses," integrating survey research with a campus carbon footprint assessment at the University of Prishtina.

To ensure institutional representativeness, a structured survey was administered across all 14 academic units, yielding a final sample of $n = 232$ (43.1% teaching staff, 44.8% students, and 12.1% administrative personnel). The questionnaire was structured into dedicated sections evaluating demographics, mobility patterns, energy-saving behaviors, recycling practices and stakeholder perceptions of university sustainability initiatives. Concurrently, environmental impacts were quantified through carbon footprint calculations covering energy, water, waste and transport sectors, utilizing standardized emission factors from Kosovo's national greenhouse gas inventory (2023–2024) [6].

This design integrates surveys, statistical analysis, and emissions accounting to correlate individual behaviors with institutional energy dynamics, informing a Green Campus framework.

4 Analysis and Discussions

This study interprets sustainability performance at the University of Prishtina through socio-technical systems and multi-level governance perspectives, emphasizing that environmental outcomes are primarily determined by institutional structures rather than individual behavior. The results consistently show that sustainability practices exist at the behavioral level but are not effectively translated into system-wide institutional performance due to structural and governance constraints.

4.1 Analysis of Energy Consumption and Carbon Footprint Assessment

The energy profile (Table 1) demonstrates a strong concentration of electricity use in laboratories, IT infrastructure, cooling systems and lighting. This reflects the functional requirements of engineering education and confirms that energy demand is embedded within the socio-technical configuration of the university system rather than shaped by individual user behavior.

From a socio-technical transition perspective, such patterns reflect regime stability and infrastructural dependency, where established technical systems constrain transformation pathways. In Kosovo's carbon-intensive electricity system 1.34 kg of co_2, this structural dependence significantly amplifies emissions. The percentage contribution was calculated as the ratio of measured annual emissions from the Faculty of Mechanical Engineering (FME) and the estimated total University of Prishtina emissions relative to the national greenhouse gas inventory reported for Kosovo (2023–2024), ensuring consistent unit conversion and system boundary alignment.

Table 1. co_2 emissions from the FME building and from all UP units

co2 emission factor (kg • co2/kw • *h*)	1.34
energy consumption (kw • *h*/year)	34918
total co2emission (kg • co2)	46790.12
total (mton/year)	$4.67901 \bullet 10^{-5}$
total in kosovo (mton/year)	5.68
% fme s*h*ares wit*h*in kosovo	0.00082%
% up s*h*ares wit*h*in kosovo	~0.01148%

4.2 Resource Consumption and Digital Transition

Thermal energy data (Fig. 1) indicate seasonal demand fluctuations and inefficiencies linked to outdated heating systems and limited automation, reinforcing the role of infrastructure rather than user behavior in energy losses.

Digital transformation introduces a dual effect, while reducing paper consumption, it increases electricity demand for related ICT devices. This produces a compensatory consumption consistent with efficiency rebound theory, where gains in material efficiency are offset by higher energy use in digital systems. These findings demonstrate that digitalization does not fundamentally improve sustainability outcomes unless accompanied by governance mechanisms that regulate energy consumption across ICT infrastructures.

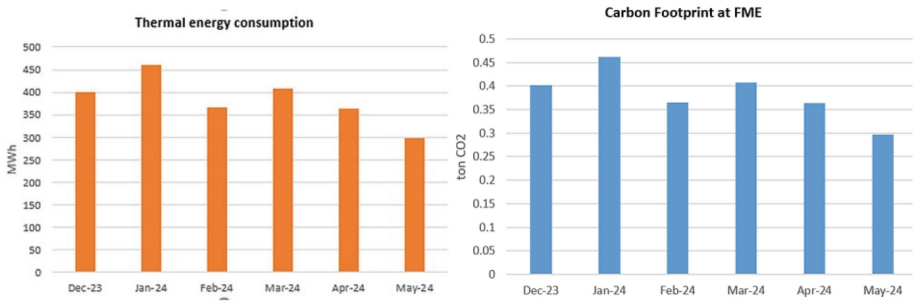


Fig. 1. a) Monthly thermal energy consumption (kWh) by building zone, for 2024, b) Monthly carbon footprint (kg CO_2) over the reporting period.

4.3 Mobility, Operations and Education

Figure 2 presents mobility patterns among students, teaching and administration staff, including average travel distance and transport mode distribution. The results show that despite relatively short travel distances, private car use remains dominant, while the share of public transport and shared mobility is comparatively low.

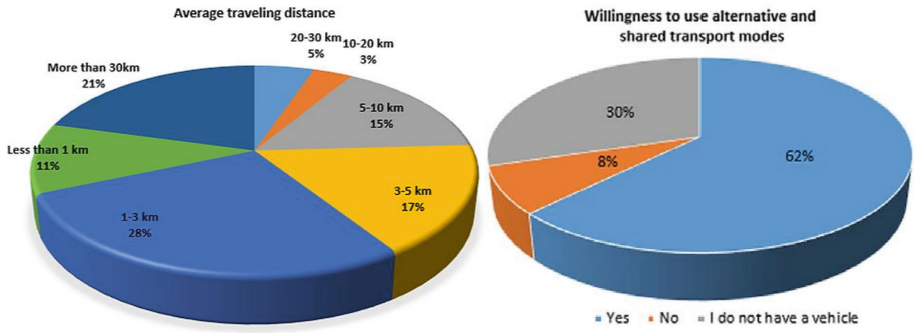


Fig. 2. a) Average travelling distance b) Distribution of alternative and shared transport modes (n = 232, 43.1% teaching, 44.8% students, 12.1% administrative staff).

Figure 3 illustrates sustainability practices within university operations, including energy-saving behavior, waste reduction and resource reuse. The findings show a high level of individual engagement in energy-saving actions, however, structured institutional practices such as systematic recycling and resource management remain limited. This suggests a gap between individual behavior and institutional operational systems. Operational sustainability is uneven, with strong individual practices but weak system-level implementation.

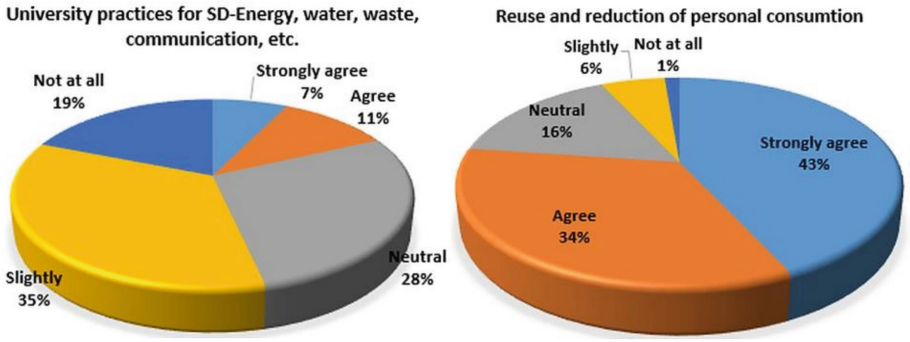


Fig. 3. a) Individual energy-saving and waste-reduction practices, b) Reuse and resource reduction practices (n = 232).

Figure 4 presents perceptions and actions related to sustainability integration in education. The results indicate that while awareness of sustainability topics is relatively high, their integration into formal curricula remains inconsistent and dependent on individual academic initiatives rather than standardized program structures.

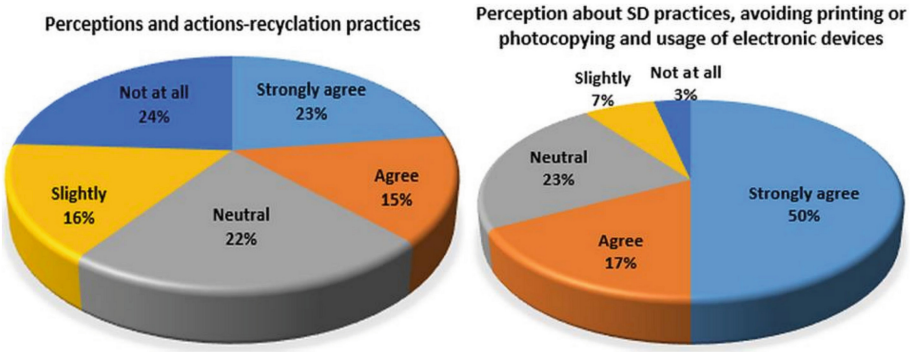


Fig. 4. a) Perceptions and actions related to sustainability integration, b) Perceptions about sustainable practices (n = 232).

4.4 Cross Domain Synthesis and Systemic Interpretation

Across all domains, results show strong individual sustainability awareness but weak institutional capacity to scale or integrate practices, indicating a clear micro and meso misalignment consistent with socio-technical transition theory. Carbon footprint findings confirm that impacts are driven mainly by structural energy dependencies rather than behavior, making sustainability a system-level outcome shaped by infrastructure, operations and governance.

In general, sustainability in higher education emerges as a socio-technical system property rather than individual action, shifting the focus from behavior change to institutional transformation. These findings align with Valls-Val and Bovea [4], whose review of carbon footprint studies in higher education identified that energy consumption is dominated by operational infrastructure rather than occupant behavior and that governance capacity is the primary differentiator between high and low performing institutions. The concentration of electricity demand in laboratories and IT systems is further consistent with Hong et al. [15], who found such spaces account for 40–60% of total university electricity use regardless of climate zone or institutional size. In contrast to Stough et al. [12], who reported relatively high levels of formal sustainability curriculum integration at Western European universities, this study confirms that sustainability education at the University of Prishtina remains decentralised and initiative-dependent, reflecting a meso-level governance deficit common to universities in transitional institutional contexts.

4.5 Implications for Green Campus Transformation

Effective sustainability transition in higher education requires a shift from behavior-focused actions to governance-driven system redesign. Transformation depends on aligning infrastructure, operations and academic governance into a coherent institutional system. In transitional contexts such as Kosovo, the main barrier is not awareness but limited institutional capacity for coordination, reflecting systemic barriers to scaling sustainable practice. The Green Campus transition therefore, requires institutional reconfiguration through alignment of technical, administrative and educational systems. Regarding transferability, elements of the Green Campus model vary in their context-specificity. Kosovo's high emission factor (1.34 kg co_2/kw*h* vs. EU average 0.25–0.3 kg co_2/kw*h*) means that the energy and decarbonisation objectives in Table 2 yield disproportionately larger emission reductions here than at comparable European institutions, these should be recalibrated to the local emission factor when applied elsewhere. Conversely, the governance, curriculum integration and mobility domains address structural challenges and coordination deficits, decentralised decision-making, infrastructure-dependent behaviour as documented across higher education systems at different income levels and energy contexts [10, 11]. These elements are therefore broadly transferable to other universities in transitional economies, while institutions in high-income EU countries may apply the governance architecture of Table 2 as a benchmarking tool with recalibrated KPI thresholds.

4.6 Development of the Green Campus Framework

The Green Campus framework translates empirical findings into an integrated implementation model linking objectives, indicators, responsibilities, timelines and monitoring (Table 2). It functions as a governance system aligning energy, resources, mobility, education and institutional management within a unified sustainability structure, supported by carbon accounting, energy audits and digital dashboards in line with EU.

Green Deal and SDG targets. The model comprises interdependent domains: energy and emissions, resource efficiency and circularity, sustainable mobility, curriculum integration and governance and monitoring, reflecting the interconnection of technical, operational and institutional dimensions of university sustainability.

Implementation is defined through KPIs and assigned responsibilities to ensure accountability and comparability. Table 2 operationalizes the framework into measurable actions for monitoring and policy tracking across university units.

Table 2. Green campus governance model for the technical faculty

Strategic objective	KPI (EU/SDG-aligned)	Responsible actors	Timeline	Monitoring method	Expected impact	EU Green Deal/SDG link
Reduce energy consumption	kWh/m^2/year reduction	Energy manager, administration	1–3 yrs	Smart meters, energy audits	Lower energy demand	EU Energy Efficiency Directive: SDG 7, 13
Expand renewable energy	% renewable electricity	Faculty + partners	2–5 yrs	PV (photo voltaic) production data	Grid dependence reduction	EU Green Deal Clean Energy: SDG 7, 13
Improve water efficiency	Liters/person/day	Facility management	1–3 yrs	Water meters	Reduced water use	EU Circular Economy Action Plan: SDG 6
Strengthen waste circularity	% waste recycled	Sustainability office	1–2 yrs	Waste audits	Reduced landfill impact	EU Circular Economy Strategy: SDG 12
Sustainable mobility transition	% low-carbon commuting	Campus mobility unit	2–5 yrs	Mobility surveys	Lower transport emissions	EU Sustainable Mobility Strategy: SDG 11,13
Integrate sustainability incurricula	% courses updated	Academic departments	2–4 yrs	Curriculum review	Green skills development	EU Green Skills Agenda: SDG 4, 13
Strengthen sustainability governance	Sustainability office operational	Rectorate/Dean's Office	1 yr	Governance KPIs	Institutional coordination	EU Governance for Sustainability: SDG 16

5 Conclusions

The results indicate that sustainability performance at the University of Prishtina is shaped more by structural and institutional conditions than by individual behavior. This study provides empirical evidence on energy use and sustainability practices in a higher education setting within a transitional context, highlighting the importance of institutional coordination and operational capacity for efficient resource management and environmental performance. Improving sustainability outcomes requires infrastructure modernisation, administrative coordination and the integration of energy considerations into routine institutional processes. These findings are particularly relevant for higher education systems under resource and governance constraints. The study contributes to the literature on socio-technical transitions in higher education by showing how institutional capacity conditions the effectiveness of sustainability actions. It suggests that embedding sustainability within university governance, supported by digital monitoring and performance-based accountability, can accelerate this transition. Future research should extend this framework to multi-university comparisons to validate its transferability across different institutional and infrastructural contexts.

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Existing Methods for Stress–Strain Analysis of Masonry Vaults and Numerical Investigation of Crack Formation Mechanisms in Historical Masonry Vaults for Sustainable Reconstruction and Heritage

Dina Khaliullina(✉)

Moscow State University of Civil Engineering (MGSU), Moscow, Russia
khaldin.global@gmail.com

Abstract. This paper presents a study of existing stress–strain analysis methods for masonry vaults and a numerical investigation of crack formation mechanisms in historical masonry structures. The research focuses on cylindrical and groin vaults of a cultural heritage building in Kazan, constructed from clay brick masonry. Traditional analytical approaches developed for vaults in the 18th–20th centuries are reviewed in order to establish a methodological basis for modern numerical modelling. A finite element model was developed in LIRA to simulate the behaviour of masonry vaults under self-weight and under several degradation scenarios, including differential settlement, support displacement, and partial volume shifting. Material parameters were defined based on in-situ testing. The results indicate that diagonal cracking patterns primarily arise from differential settlement of the supporting structures, which corresponds to the observed cracking on site. Additional crack initiation was registered under rotational and lateral support movements, demonstrating the sensitivity of masonry vaults to loss of spatial stiffness. The numerical results closely reproduced real crack patterns and allowed identification of the most probable structural causes

The study enables identification of the actual causes of cracking in masonry vaults and supports the design of strengthening measures in critical zones only, thereby optimising reconstruction costs while preserving historical heritage. In addition, preliminary numerical analysis makes it possible to predict crack locations before visible damage occurs and to strengthen vulnerable structural elements, such as foundations. The results demonstrate that sustainable reconstruction and conservation of historical masonry vaults should be addressed through a comprehensive structural assessment

Keywords: Historical masonry vaults · Vault analysis methods · Crack formation mechanisms · Finite element modelling · Sustainable reconstruction

Brick masonry vaults of historical buildings represent complex spatial thrust systems whose structural behaviour largely depends on the condition of the supporting contour and the foundation. In the reconstruction of cultural heritage buildings, a key task is not

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only the restoration of the load-bearing capacity of the structures but also the preservation of their original material fabric with minimal intervention. This requires a justified identification of the causes of crack formation in order to avoid excessive strengthening measures and unnecessary dismantling.

This study examines the vaults of a cultural heritage building located in Kazan, including a cylindrical vault in the basement in axes B–C/1–2 and a groin vault on the first floor in axes A–B/5–6. According to the results of the structural survey, diagonal cracks with an opening width of up to 2 mm were identified in the masonry of the vaults [1]. The aim of this work is to determine the causes of crack formation in the vaults and to develop strengthening measures in the necessary zones, thereby optimising reconstruction costs while preserving the historical heritage.

Masonry vaults are generally subjected to loads from their self-weight as well as from the structural elements located above them, including environmental effects [2]. Under loading, a vault mainly works in compression. The resulting vertical compressive forces are transferred to the supports. In many types of vaults an additional horizontal force arises, meaning that the structure also develops thrust. This horizontal thrust may be relatively small or may be resisted by a ring tie or other reinforcement embedded within the body of the vault.

The objective of the research is to identify the mechanism of crack formation in the considered vaults through numerical modelling of different deformation scenarios of the supporting contour. The obtained results make it possible to determine the most probable causes of the observed damage and to justify local strengthening measures aimed at extending the service life of historical structures.

In the context of sustainable and circular reconstruction, the application of numerical modelling makes it possible to minimise unnecessary structural intervention and to preserve the original masonry fabric of historical buildings. Identification of the actual causes of crack formation supports targeted strengthening of structurally vulnerable zones only, reducing excessive demolition, material consumption, and construction waste.

1 Existing Methods for the Stress–Strain Analysis of Masonry Vaults

Masonry vaults represent complex spatial thrust systems whose structural behaviour is governed primarily by compressive stress transfer and horizontal thrust acting on the supporting contour. Due to the heterogeneous structure of masonry and the variability of material properties, accurate analytical evaluation of the stress–strain state of vaults remains a challenging engineering task. The structural behaviour of vaults depends not only on their geometric parameters but also on the stiffness of the supporting structures and the interaction between individual masonry elements. For this reason, the analysis of masonry vaults has historically been based on simplified analytical approaches derived from empirical observations and structural mechanics.

The earliest approaches to the design and assessment of masonry vaults were based on empirical formulas developed from observations of historical structures [3]. Researchers such as Lesquillier, Rankine and Kerner proposed relationships for estimating vault

thickness and geometric proportions depending on the span and rise of the vault. These empirical formulas were derived from the analysis of long-term performance of masonry structures and were intended primarily for preliminary design. Later studies by Rondelet and Schwarz refined these approaches by introducing parameters related to the ratio between loading and allowable compressive stresses in masonry [3, 4]. However, such empirical methods often lead to conservative design solutions and do not fully account for the complex interaction between loads, geometry and material properties.

Further development of analytical methods was associated with the application of the limit equilibrium theory [5]. According to this concept, the safety of a masonry vault is assessed by analysing the position of the thrust line within the masonry section. If the thrust line remains within the middle third of the section, tensile stresses are avoided and the vault remains stable.

Another analytical approach was proposed by Onishchik, who developed a method based on equilibrium equations in so-called "dangerous sections" [5]. In this method, the internal forces in characteristic sections of the vault are determined and subsequently verified for eccentric compression and shear resistance.

Although these analytical approaches provide valuable insight into the behaviour of masonry vaults, they involve significant simplifications and cannot fully represent the complex stress–strain state of spatial masonry structures. Therefore, modern research increasingly relies on numerical modelling methods, particularly the finite element method, which makes it possible to analyse complex structural behaviour and to simulate crack formation mechanisms in masonry vaults [6].

2 Case Study. Investigated Structure

The object of the study is a cylindrical vault of the basement located in axes B–C/1–2 and a groin vault of the first floor located in axes A–B/5–6. According to measurements obtained during the structural survey, the vault thickness ranges from 270 mm to 300 mm depending on the thickness of the plaster layer. The vaults and walls of the basement and the first floor are constructed of solid clay brick masonry with brick grades ranging from M25–M50 to M75 and lime–sand mortar with grades from M15 to M25–M50, as presented in Tables 1 and 2 [1], according to masonry design standards [7].

The brick vaults of the basement and first-floor intermediate floors perform a dual structural function:

– ensuring the overall spatial stiffness of the building;
– carrying a part of the vertical service loads acting on the floors.

Therefore, the removal of the brick vaults even in local areas, not to mention their complete dismantling throughout the building, would lead to a loss of the spatial stiffness of the structure and potentially to the collapse of the building.

In the basement vaults located in axes B–C/1–3, a system of cracks with an opening width of up to 2.0 mm was identified, as well as a crack with an opening width of 4.0 mm in axes B–C/4–5. In the first-floor vaults located in axes A–B/2–3, B–C/3–4 and A–B/4–5, a system of cracks with an opening width of up to 5.0 mm was observed. According to Clause 3 [8, 9], the condition of the vaults is assessed as limited serviceability. The

Table 1. Results of strength testing of structures in axes B–C/1–2 in the basement

No.	Material	Test location	R, MPa	Actual grade
1	Basement walls, Clay brick	C/1-2	11.1	M 75
2	Basement walls, Lime mortar	C/1-2	3.9	M 25
3	Basement vaults, Clay brick	B-C/1-2	12.3	M 75

Table 2. Results of strength testing of structures in axes A–B/5–6 on the first floor

No.	Material	Test location	R, MPa	Actual grade
1	First-floor walls, Clay brick	A-B/5-6	10.9	M 75
2	First-floor walls, Lime mortar	A-B/5-6	-	M 25
3	First-floor vaults, Clay brick	A-B/5-6	10.9	M 75

defect maps are shown in Figs. 1 and 2, and the symbols used for crack identification are presented in Table 3.

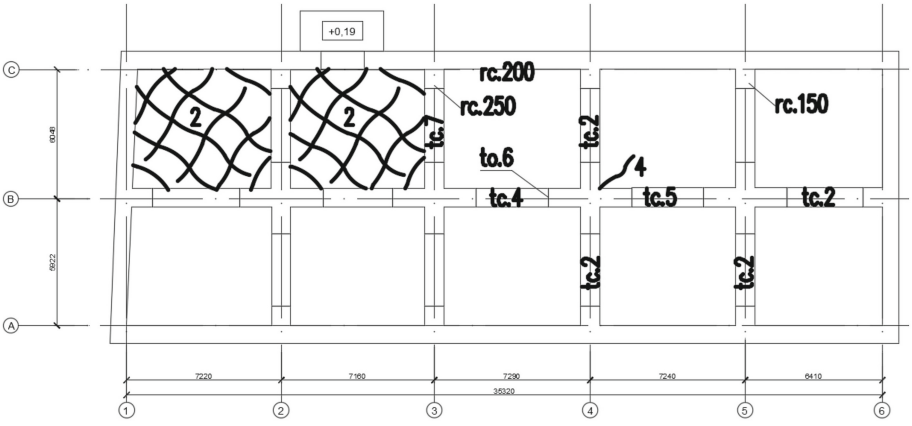


Fig. 1. Defect map of the basement vaults.

One of the most common types of damage in masonry structures is cracking. According to statistical data, the most frequent causes of crack formation in masonry structures are:

- differential settlement of foundations (65–75%);
- structural overloading (10–15%);
- temperature deformations (10–15%);
- moisture-related deformations (5–8%);
- special loads and impacts (2–5%).

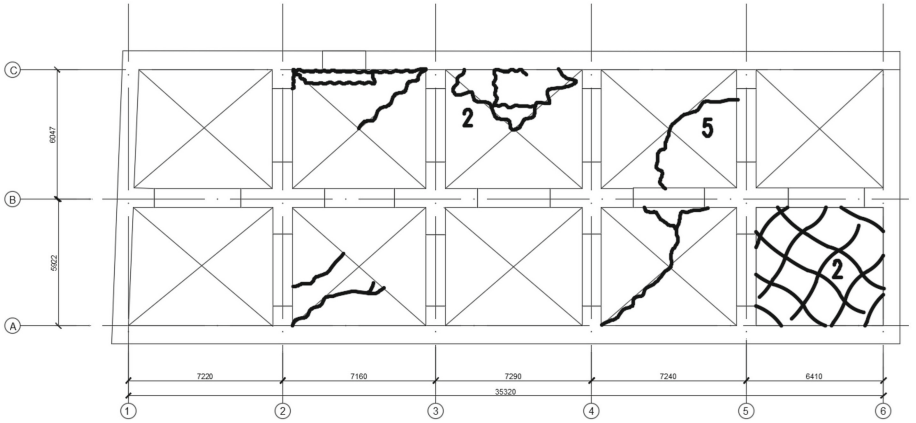


Fig. 2. Defect map of the first-floor vaults.

Table 3. Defect symbols used in the crack map

Symbol	Description
tc.1	Crack at the crown of the vault (crack width 1 mm)
to.1	Crack at the support of the vault (crack width 1 mm)
rk.100	Masonry damage with a depth up to 100 mm
1	Crack (or crack system) with a crack width of 1 mm

According to the conducted structural survey, it is necessary to restore the spatial stiffness of the building and the load-bearing capacity of the brick vaulted floor structures of the basement and the first floor. For this purpose, it is necessary to identify the causes of crack formation and to strengthen the required structural elements.

3 Research Methodology in the LIRA Software Package. Research Program

For the structural analysis, the LIRA software package was used. The software implements the finite element method (FEM), which is an efficient numerical method for solving a wide range of boundary value problems of a continuous medium. The method is based on replacing the investigated structure with a finite number of discrete elements connected at nodes.

During the development of the computational model, quadrilateral, rectangular, and triangular spatial finite elements were used (Fig. 3). The cylindrical vault model consists of 290 elements, while the groin vault model consists of 316 elements.

The numerical experiment included two sequential analyses:

– behavior of the cylindrical and groin vaults under self-weight loading;

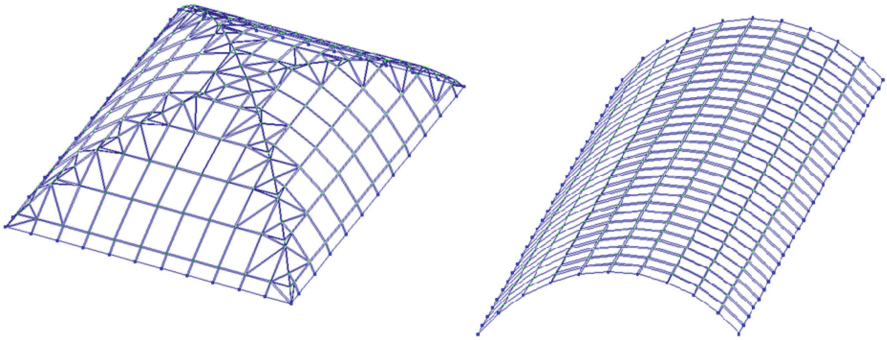


Fig. 3. Masonry groin vault and cylindrical vault models.

– behavior of the vaults with the introduction of a failure factor.

The aim of the study was to reproduce diagonal cracks corresponding to the defect map. To achieve this, the following scenarios were simulated:

– sequential displacement of the corner of the support contour;
– shear displacement of part of the structure volume;
– settlement of the support.

The simulated deformation scenarios were selected based on characteristic crack formation mechanisms in masonry vault systems reported in previous studies and structural survey observations.

4 Results

According to the obtained results, failure under self-weight does not occur. Both the groin vault and the cylindrical vault work in compression. The vault thickness adopted during the design stage may therefore be considered optimal.

A fragment of the internal forces in shell elements of the cylindrical vault under support settlement is presented in Table 4. For each element, the following parameters are given: N_X – normal stress along axis X_1; N_Y – normal stress along axis Y_1; M_X – bending moment acting on the section orthogonal to axis X_1; M_Y – bending moment acting on the section orthogonal to axis Y_1. Based on these data, it is possible to determine in which elements cracks are formed.

Visualization of the formed cracks was carried out for groin and cylindrical vaults under all conditions of crack formation, namely sequential displacement of the corner of the support contour, shear displacement of part of the structure volume, and settlement of the support.

As a result, under settlement of the support, cracks were obtained that coincide in location with those observed in the structure. It was established that crack formation in the cylindrical vault located in axes B–C/1–2 of the basement occurs due to differential foundation settlement, while crack formation in the groin vault located in axes A–B/5–6

Table 4. Internal forces in shell elements of the cylindrical vault under support settlement (fragment)

Element No.	N_x (t/m^2)	N_y (t/m^2)	M_x (t)	M_y (t)	Crack formation at $\sigma_x > 0.05$ MPa	Crack formation at $\sigma_y > 0.05$ MPa
1	16.085	−2.682	0.333	−0.023	yes	no
2	−1.335	3.399	0.338	−0.143	no	no
3	−22.267	−10.395	−1.366	−0.026	no	no
4	−5.721	−11.553	−1.193	0.000	no	no
5	−1.353	−2.253	0.173	−0.029	no	no
6	−0.528	−0.064	−0.024	0.004	no	no
7	−0.308	0.443	0.013	0.008	no	no
8	−0.419	0.048	0.005	0.010	no	no
9	−0.584	−0.629	0.003	0.008	no	no
10	−0.704	−0.602	0.003	0.004	no	no
11	9.331	−9.693	0.233	−0.224	yes	no
12	−2.264	4.811	0.127	−0.402	no	no

of the first floor occurs due to cracks in the supporting walls, which in turn were caused by a weak foundation.

The obtained result corresponds to the results of the structural survey; the building has a rubble foundation, which will subsequently be strengthened. The numerical results demonstrated qualitative agreement with the crack patterns identified in the structural survey and defect maps.

During the study, the causes of crack formation in the remaining vaults were also identified. In the vaults located in axes B–C/4–5 of the basement and A–B/2–3 of the first floor, crack formation occurs due to sequential displacement of the corner of the support contour. In the vaults located in axes B–C/2–3 and B–C/3–4 of the first floor, crack formation occurs due to shear displacement of part of the structure volume.

5 Conclusions

Numerical modelling using the finite element method made it possible to reproduce different scenarios of vault behaviour under settlement of the support, sequential displacement of the corner of the support contour, and shear displacement of part of the structure volume. It was established that under the action of self-weight failure does not occur, and the formation of diagonal cracks is mainly associated with differential foundation settlement and the loss of stiffness of the supporting walls. The numerical analysis demonstrated the sensitivity of masonry vaulted systems to support settlement, sequential displacement of the corner of the support contour, and shear displacement of part of the structure volume.

Comparison of the numerical modelling results with the defect map showed a correspondence between the calculated zones of tensile stresses and the cracks actually identified in the structure. This made it possible to determine the most probable causes of the damage and to establish the priority of strengthening the structural elements.

The application of numerical analysis at the stage of reconstruction design makes it possible to identify cause-and-effect mechanisms of damage, prevent excessive intervention in historic masonry, and limit strengthening works to local zones only. Such an approach supports sustainable and circular reconstruction by preserving the original material fabric of heritage buildings, reducing construction waste and unnecessary material consumption, and extending the operational life cycle of existing structures.

The use of the finite element method in the analysis of complex spatial thrust systems made of brick masonry provides a deeper understanding of structural behaviour under the combined interaction of building elements. This is particularly important when working with cultural heritage structures, where the causes of crack formation are not always obvious and require comprehensive engineering analysis. The study focuses on identifying the most probable crack formation mechanisms rather than simulating the full long-term damage evolution of the masonry vaults.

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Experimental Assessment and Modelling of Natural Ventilation Strategies in a University Office: Effects on Indoor Air Quality and Thermal Conditions

Manuela Almeida[1], Fabrizio Ascione[2], Gabriela Barbosa[1], Teresa Iovane[2(✉)], Gerardo Maria Mauro[3], and Sandra Monteiro Silva[1]

[1] Department of Civil Engineering, ISISE, University of Minho, Guimarães, Portugal
[2] Department of Industrial Engineering, Università degli Studi di Napoli Federico II, Napoli, Italy
teresa.iovane@unina.it
[3] Department of Architecture, Università degli Studi di Napoli Federico II, Napoli, Italy

Abstract. The existing building stock needs to undergo an extensive retrofit process to meet the decarbonisation targets set by European directives, and university/educational buildings have characteristics that make them a complex category. Namely, it is essential to ensure an effective balance among indoor air quality, energy performance, operational sustainability, and, moreover, the ability to remain resilient to the impacts of climate change. In this study, an experimental investigation is conducted in a university office located in a Mediterranean climate. Indoor environmental parameters were monitored under different operating conditions, including unoccupied periods, typical occupancy patterns, and natural ventilation strategies based on thermal comfort and CO_2 levels. The analysis enabled estimation of the building's natural infiltration rate and evaluation of the effectiveness of manual and demand-controlled natural ventilation approaches. The collected data provided an experimental basis for developing a calibrated indoor environmental model of the investigated office, which reproduced the main measured CO_2 trends under the monitored operating conditions. The calibrated model can support future investigations of ventilation strategies aimed at improving indoor air quality while reducing thermal discomfort under different seasonal and climate conditions. Overall, the study provides a basis for the future assessment of ventilation strategies in university office buildings

Keywords: Energy Efficiency · University Building · Indoor Air Quality · Thermal Comfort · Ventilation Strategies

1 Introduction

The building sector is internationally recognised, at European and national levels, as highly energy-intensive and, for this reason, has been at the centre of policies aimed at improving its energy and, consequently, environmental performance for more than

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25 years. With the latest revision of the European Energy Performance of Buildings Directive (EPBD 2024/1275), to achieve a zero-emission building stock by 2050 [1], Member States are required to prepare a national building renovation plan and to establish minimum energy performance requirements.

Indoor air quality (IAQ) was already addressed in the previous version of the Directive (2018/844) [2], but in the latest revision, it assumes an increasingly central and recognised role. Both the national plan and the minimum performance requirements must account for indoor air quality to ensure an appropriate balance between energy efficiency and healthy indoor conditions.

Several studies have related IAQ to human health and performance [3, 4], and for this reason, a wide range of research activities focusing on the monitoring of indoor air contaminants have been conducted in the last decade. Since it is recognised that there is an impact on work and learning performance, monitoring campaigns are conducted in schools, offices, and even residential environments to correlate the evolution of indoor pollutants with occupants' perceptions and productivity.

Most studies of IAQ are based primarily on experimental campaigns. In this study, the objective is to develop a model calibrated with measured data to subsequently test various strategies aimed at improving indoor conditions. The monitoring campaign was conducted in an office zone within a university building under different operating conditions. Indoor air temperature and CO_2 concentrations are discussed. The measured data were used to calibrate the office model, which can serve as a starting point for testing a wider range of possibilities to achieve the best trade-off between indoor air quality and energy efficiency. Moreover, building energy simulation tools, such as EnergyPlus, enable modelling and evaluation of indoor CO_2 concentrations and generic contaminants. The measured data could be used to identify correlations between CO_2 and other pollutants, and the simulated CO_2 from the calibrated model may then be used as an indicator for a preliminary evaluation of ventilation adequacy and occupancy-related indoor air quality conditions.

2 Case Study

The study was conducted in an office zone within a university building in Naples, Italy, with a Mediterranean climate (Italian climate zone C).

The building under investigation is one of the University of Naples Federico II's engineering facilities. Built between 1956 and 1965, it houses classrooms for teaching, student services offices, study rooms, laboratories, and offices for teaching and research staff (Fig. 1A). It has a reinforced concrete structure. The thermal transmittance (U-value) for external walls is 0.89 W/m^2K, while the U-values for the roof and ground floor are 1.00 W/m^2K and 0.92 W/m^2K, respectively. With reference to the transparent building envelope, double-glazed windows with a thermal transmittance value of 3.2 W/m^2K and an aluminium window frame without a thermal break are installed. The monitoring campaign was carried out in an office located on the 11th floor of the building (highlighted in yellow in Fig. 1A, and detailed in Fig. 1B) facing west.

Environmental parameters affecting indoor air quality were monitored over two weeks in March 2026 using an air-Q Pro sensor, which allows the measurement of

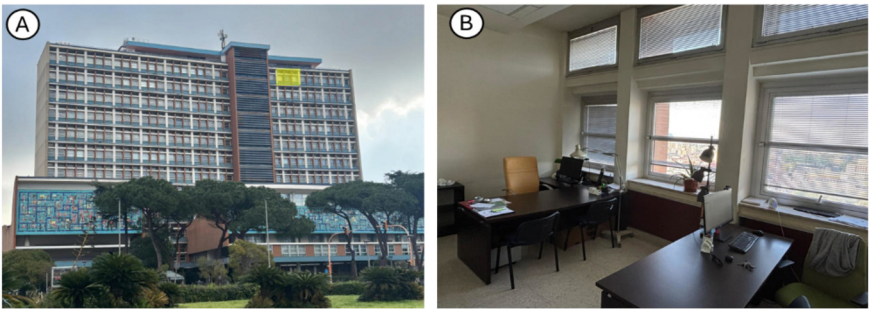


Fig. 1. Engineering facilities of the University of Naples Federico II, Italy with highlighted office investigated (A), office (B).

parameters related to thermal comfort, such as air temperature and relative humidity, as well as other variables affecting indoor environmental quality, including indoor carbon dioxide concentration, carbon monoxide, oxygen, particulate matter, nitrogen dioxide, ozone, volatile organic compounds, formaldehyde, and noise.

Regarding the outdoor climatic conditions during these two weeks of monitoring, air temperature ranged between 8 °C and 20 °C. The lowest temperatures were recorded during nighttime, between 3:00 and 6:00, while peak values occurred between 13:00 and 15:00. Temperature trend was relatively gradual during both the increase and decrease phases, whereas the relative humidity varied between 60% and 70%.

The monitoring campaign was conducted under different conditions; the following ones were analysed in this study:

- during a weekend, with no occupancy and with both windows and the door closed. Several other days under this configuration have been monitored;
- on a weekday, with a variable number of occupants, mainly with the windows and door closed. In the afternoon, due to indoor thermal discomfort reported by the occupants, one window was opened for one hour;
- on a weekday, with a variable number of occupants, with the door closed and several window-opening strategies adopted, initially based on the indoor CO_2 levels recorded and subsequently in response to thermal discomfort reported by the occupants.

Occupancy during weekdays varied due to occasional entries and exits by other occupants, as described in detail in the analysis of the monitored data.

These tests, characterised by different operating conditions, make it possible to evaluate the natural infiltration of the building during unoccupied periods with fixed window and door positions, the accumulation of CO_2 due to occupancy, and the efficacy of ventilation strategies driven by thermal comfort and CO_2 levels.

Although a wide range of indoor air quality parameters was monitored, the present study focuses on CO_2 as a tracer of occupancy and ventilation. The analysis of additional pollutants will be addressed in future work. CO_2 concentration was used to calibrate the dynamic model of the office space developed in DesignBuilder® and simulated in EnergyPlus. The model will serve as a basis for exploring ventilation strategies that

improve indoor air quality while limiting thermal discomfort, and for investigating their effects on energy demand.

3 Results

3.1 Weekend Test

The trends for indoor air temperature and carbon dioxide concentration from Friday afternoon to Monday morning are shown in Fig. 2.

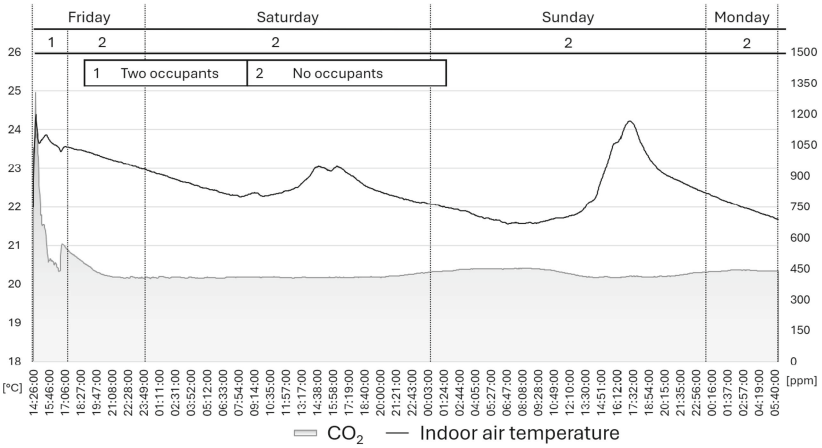


Fig. 2. Trend of indoor air temperature and CO_2 concentration within the office during the weekend.

On Friday afternoon, until around 17:00, occupants remained in the office. Due to the high indoor temperature, around 24 °C, one of the windows was opened, involving a reduction in CO_2 concentration and a slight temperature decrease. From 17:00 onwards, the office remained unoccupied with door and windows closed. CO_2 concentration gradually decreased until it reached a stable value, with slight fluctuations, mainly due to infiltration. Indoor air temperature showed a daily fluctuation, with peak values in the afternoon, consistent with the office's west-facing exposure, characterised by increased solar gain in the early afternoon.

This type of monitoring allows the evaluation of the natural infiltration rate using the CO_2 decay method [5, 6], assuming a well-mixed indoor air and a constant outdoor CO_2 concentration of around 400 ppm (Eq. 1).

$$\frac{dC_{in}}{dt} = ACH(C_{out} - C_{in}) \tag{1}$$

where C_{in} and C_{out} C_{out} are the indoor and outdoor CO_2 concentrations, respectively, and ACH is air changes per hour (h^{-1}).

Monitoring under these conditions was repeated multiple times to account for the dependence of natural infiltration on outdoor conditions, such as wind intensity and the

temperature difference between indoor and outdoor environments [7]. The evaluation of ACH was conducted in accordance with ASTM E741 [8], considering a significant portion of the decay curve in which $\ln(C_{in} - C_{out})$ exhibits a linear trend. Only cases with a sufficiently high initial concentration difference (≥ 350 ppm) were selected. The results indicate an air change rate of 1.18 ± 0.14, with variability fully consistent with previous studies [7].

3.2 Weekday Test – Typical Office Use and Strategy for Natural Ventilation Based on Occupant Comfort

During the first monitored weekday, the office was occupied for approximately 8 h by a variable number of people, ranging from 2 to 4, as shown in Fig. 3.

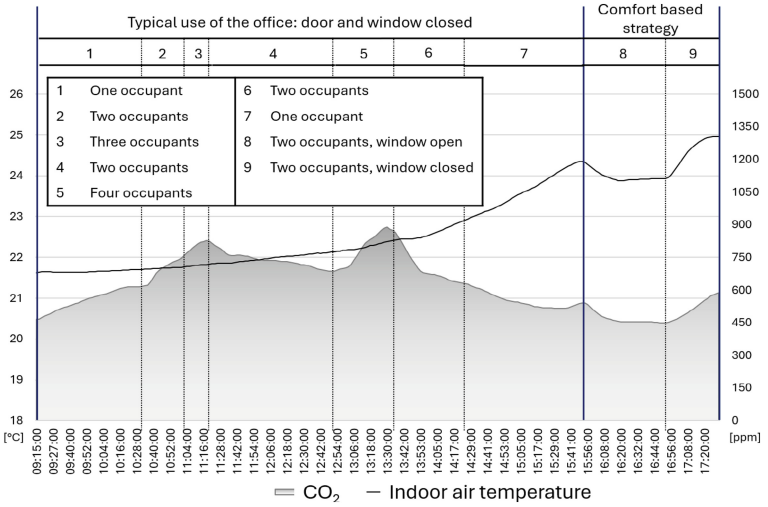


Fig. 3. Trends of indoor air temperature and CO_2 concentration in the office during a weekday under typical occupancy conditions.

For most of the day, doors and windows remained closed, and the only variations concerned the number of occupants. An increase in CO_2 concentration was observed with increasing occupancy, reflecting metabolic emissions. In the afternoon, around 16:00, due to thermal discomfort caused by the high indoor temperature, one window was opened for about an hour, resulting in a reduction in CO2 concentration and a decrease in air temperature of about 1 °C.

3.3 Weekday Test – Typical Office Use and Strategies for Natural Ventilation Based on CO_2

During the second monitored weekday, no strategy was adopted in the first four hours, similarly to the previous day (Sect. 3.2), and a very similar trend was observed (Fig. 4).

From 12:00 onwards, a CO_2-based natural ventilation strategy was adopted, with a threshold of 800 ppm for window opening. Once this value was reached, one window was opened for 30 min, resulting in a reduction of around 300 ppm.

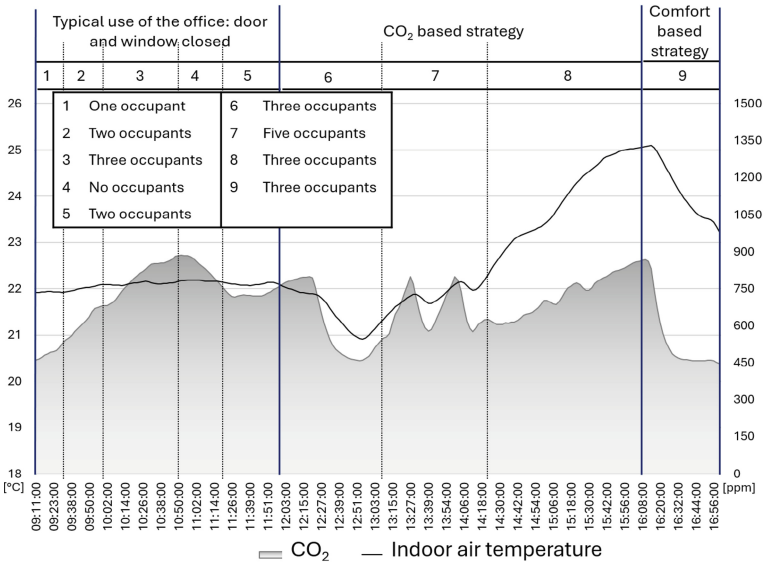


Fig. 4. Trends of indoor air temperature and CO_2 concentration in the office during a weekday under typical occupancy conditions, with CO_2-based and comfort-based natural ventilation strategies.

Then, from 13:00 onwards, a threshold for window closing of 600 ppm was established. Under high occupancy, from three to five occupants (phase 7 of Fig. 4), the 800 ppm threshold was frequently and rapidly reached, requiring repeated window-opening cycles. Approximately 10 min were required to reduce the CO_2 concentration by about 200 ppm (achieving the threshold for window closing of 600 ppm). However, with five occupants in the office, the concentration returned to 800 ppm in approximately 20 min. The CO_2 control strategy is effective, but under high occupancy conditions, frequent natural ventilation cycles are needed.

Moving to phase 8, with three occupants, the CO_2 concentration returned to 800 ppm after approximately 70 min. In the final phase (phase 9), the window was opened even after the concentration dropped below the 600 ppm threshold because elevated indoor temperatures caused thermal discomfort for the occupants.

The opening of window, and thus natural ventilation, also affected other pollutants. For example, trends in PM2.5 and PM10 during phases 7 and 8 are shown in Fig. 5. The increase in particulate matter during window opening highlights the need to balance CO_2 dilution benefits against possible increases in exposure to outdoor particles when optimising IAQ.

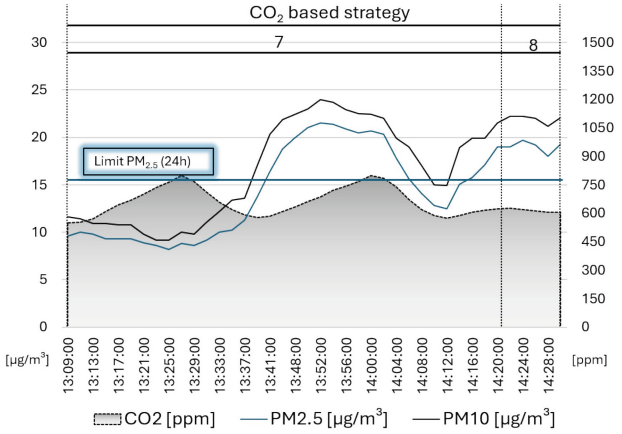


Fig. 5. Trends of indoor CO_2 concentration and PM2.5 and PM 10 in the office during a weekday under typical occupancy conditions, with CO_2-based natural ventilation strategy.

4 Calibrated Model on CO_2 Concentrations

The results of the monitoring campaign provide a robust experimental basis for calibrating a dynamic building energy model developed in EnergyPlus. The data concerning the natural infiltration (ACH) achieved in Sect. 3.1 were used, specific schedule for occupancy and natural ventilation were set, and CO_2 generation based on the occupants' gender and age according to [9] was assigned. About outdoor conditions, weather file was modified using data obtained from meteorological stations. The outdoor air temperature and relative humidity, corresponding to the data shown in Fig. 6, ranged between 14–18 °C and 60–70%, respectively.

The comparison between measured and simulated indoor CO_2 for the weekday discussed in Sect. 3.3 is shown in Fig. 6.

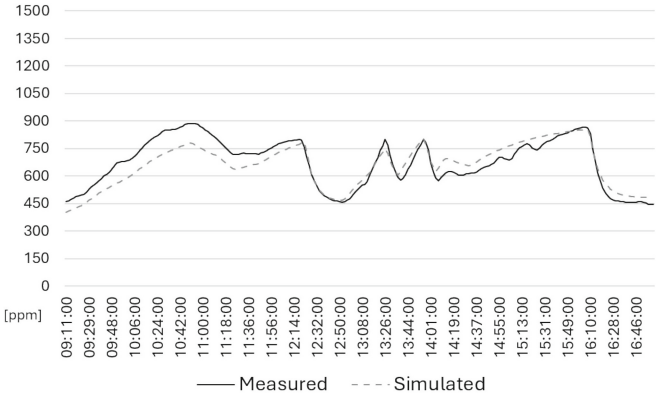


Fig. 6. Measured and simulated indoor CO_2 concentration profiles.

Overall, the model reproduces the main trend of the measured CO_2 profile and the main changes associated with occupancy variation and window-opening events discussed in Sect. 3.3.

5 Conclusions

The study presented an experimental and modelling analysis of indoor air quality in an office environment under different operating conditions. The monitoring campaign enabled the evaluation of natural infiltration rates and the assessment of natural ventilation strategies based on CO_2 concentration and thermal comfort. The calibrated dynamic model reproduced the main measured trends and can support future assessments of natural ventilation strategies under different seasonal and climate conditions. The results should be interpreted considering the short monitoring period and the fact that the analysis refers to a single office under specific operational conditions. Within these limits, the study provides a useful basis for future investigations of ventilation strategies in university office buildings.

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Advancing Urban Material Flow and Stock Analysis through City Information Modeling: Opportunities for Circularity in the Built Environment

Adriana Salles[1(✉)], Francisco Carvalho[2,3], and Luís Bragança[1]

[1] ISISE, ARISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal
adriana@civil.uminho.pt
[2] Laboratório da Paisagem, Rua da Ponte Romana, Creixomil, 4835-095 Guimarães, Portugal
[3] School of Sciences, University of Minho, Guimarães, Portugal

Abstract. Material Flow Analysis (MFA) and Material Stock Analysis (MSA) have become key approaches for understanding resource dynamics and metabolism in cities, while supporting the transition toward circular economy models. Recognized as important drivers of this transition, information technologies offer new possibilities for supporting materials analysis and achieving circularity and sustainability objectives. Technologies such as City Information Modeling (CIM) can support and promote circular economy and sustainable practices in cities. Despite the potential applications, the use of CIM for material analysis remains unexplored. Building on a prior critical analysis of the literature, this study presents a methodological framework for the use of CIM in urban material analysis. Guided by the synergies between Building Information Modeling (BIM) and Geographic Information Systems (GIS) identified in the literature, this paper explores how CIM can be applied for MFA and MSA. Furthermore, this research aims to contribute to the theoretical understanding of how digitalization can strengthen the analytical capacity of MFA and MSA and promote data-driven decision-making in circular urban planning. By bridging current methodological gaps, this study provides a conceptual foundation for integrating digital tools into future urban material analysis frameworks, paving the way toward more transparent, adaptive, sustainable, and circular cities

Keywords: Circular Economy · Urban Metabolism · Material Flow Analysis · Material Stock Analysis · City Information Modeling

1 Introduction

Cities are dynamic and complex entities that hold considerable potential to lead the transition toward climate neutrality, circular economy (CE), and sustainable development [1–3]. The CE approach offers substantial promise for addressing urban sustainability challenges by reducing waste, improving resource efficiency, and fostering economic,

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environmental, and social benefits. Cities are central players in the CE transition, offering a platform for testing innovative solutions by minimizing waste, optimizing resource flows, and enabling transformative patterns of production and consumption [4, 5]. A circular economy treats nothing as waste, but rather as a potential resource, requiring a comprehensive understanding of urban systems and their resource flows [6]. This perspective is central to urban metabolism, understood as the process by which cities extract, retain, transform, and discharge resources, which provides an overview of resource use, waste generation, and environmental impacts [7]. By treating the city as a collection of systematic and interrelated processes, metabolic analysis enables the identification of resource utilization problems and supports effective sustainability measures [8]. As interest in circular cities grows, urban systems must be understood as an integrated whole, a perspective intrinsically linked to the concept of urban metabolism, which analyses the flows, stocks, and transformations of resources through cities. Understanding material flows and stocks is particularly important for "closing, slowing, and narrowing" material loops and improving urban resource management.

The built environment accounts for roughly 35–45% of global material use and around 25% of global waste generation [12, 13], making construction-related flows and stocks particularly critical to examine. Material Flow Analysis (MFA) is defined as "a systematic assessment of the state and changes of flows and stocks of materials within a system defined in space and time" [14]. Grounded in mass-balance principles, MFA quantifies inputs, outputs, and internal flows across multiple scales and time frames and is widely applied as a flexible decision-support tool [6]. Material Stock Analysis (MSA) complements MFA by identifying and quantifying materials that remain within the socio-economic system for extended periods, such as construction materials, with stocks conventionally defined as materials with a service life of at least one year [6]. Together, MFA and MSA support efforts to close, slow, and narrow material loops, advancing resource management and sustainable urban development.

Here, digital tools play a central role in accelerating the transition towards a circular and sustainable built environment. Technologies such as City Information Modeling (CIM) can promote CE and sustainable practices within cities [9, 10]. CIM integrates diverse data sources, technologies, and analytical tools, including Building Information Modeling (BIM) and Geographic Information Systems (GIS), into a unified, intelligent city model. This integrative approach leverages multi-source urban data for comprehensive collection, integration, processing, and analysis, including material urban analysis. In this regard, BIM models contribute to the building-level material data for detailed stock calculations, while GIS can be used for spatial analysis and mapping, providing georeferenced urban data. Together, these technologies promote a holistic view of material flows in urban environments. Despite growing interest in CIM's capabilities, the literature lacks studies linking CIM to the implementation of CE strategies in urban contexts, and very few explicitly connect CIM to MFA and MSA methods [11].

To address this gap, this paper presents a conceptual framework for applying CIM to urban material analysis. Guided by BIM–GIS synergies identified in the literature, the study provides a conceptual foundation for integrating digital tools into future MFA and MSA frameworks, paving the way toward more transparent, adaptive, sustainable, and circular cities.

2 Literature Review on Digital Tools for Urban Material Analysis: Current CIM Applications

GIS and BIM, two fundamental components of a CIM environment, are extensively documented in the literature. GIS has been widely applied in MFA and MSA studies [7, 15, 16], valued for its capacity to map spatial and temporal patterns, classify building typologies, and provide spatially referenced data for estimating material stocks and flows. BIM contributes through detailed material databases and its ability to manage complex information across the building life cycle [16, 17]. Despite their individual potential, combined synergies between GIS and BIM for material analysis have been less explored in the literature.

Notably, some studies have been integrating BIM and GIS for material analysis without referencing CIM. Parezanović et al. [16] assessed building material stocks by combining BIM models with GIS cadastral data, while Triantafyllidis et al. [17] used georeferenced BIM models for MSA, observing that GIS linkage enhances spatial analysis capacity. In both cases, the technological foundations align closely with CIM principles. From the reviewed studies, only one explicitly applies the CIM concept, proposing a materiality-based city information model (mCIM) that integrates GIS and BIM datasets to develop a material cadastre map [13].

CIM remains in the early stages of conceptual and practical development. Although its potential is acknowledged in the literature, its application to CE, specifically for material analysis, in cities, remains largely unexplored. In contrast, the core technologies for CIM, namely GIS and BIM, are well established in CE, MFA, and MSA research. Many studies examine these tools separately, analyzing spatial patterns and modeling building characteristics, thus demonstrating their usefulness for estimating material stocks, for instance. When combined, their integration frequently mirrors CIM logic, even when the term is not employed, suggesting a terminological and conceptual gap attributed to the novelty and lack of a standardized definition for CIM. This reveals a clear research opportunity: to systematically apply CIM-based approaches to MFA and MSA, building on the BIM–GIS synergies already demonstrated in the literature. In this way, CIM can serve as an instrument for data-driven decision-making in circular urban governance, promoting a holistic, detailed view of material dynamics across the urban network.

3 Methodology

This study adopts a qualitative, framework-development research design, aimed at producing a conceptual contribution rather than empirical quantification. Grounded in the findings of a prior critical literature review [11], the methodology follows an inductive reasoning approach, moving from the identification of theoretical gaps and technological synergies in the literature toward the proposition of an integrated framework.

The critical literature review in the aforementioned prior work [11] examined the relationships among CIM, MFA, and MSA by addressing the research question: *"Is City Information Modeling currently defined and used in the context of Material Flow and Stock Analysis?"* The review was conducted across the Web of Science and Scopus

databases, which were selected for their breadth and quality of peer-reviewed literature. Retrieved records were screened to remove duplicates and papers unrelated to the research question. Limitations of that review include potential omission of studies from non-indexed repositories, terminological variability not fully captured by the search string, and a degree of subjectivity inherent to the screening process.

4 CIM-Based Framework for Urban Material Analysis

The proposed framework conceptualizes CIM as an integrative data infrastructure that can bridge urban-scale spatial analysis and material accounting methods. It is structured around three interconnected layers: a data input layer, aggregating georeferenced urban datasets from GIS platforms, BIM models, and open data repositories; a processing layer, where material quantities are calculated through MFA and MSA methods; and an output layer, translating analytical results into decision-support information for circular urban planning. The framework is designed around four core principles: interoperability between data formats and platforms; spatial and temporal scalability; transparency in data provenance and calculation logic; and alignment with circular economy objectives, particularly the closing, slowing, and narrowing of material loops. Figure 1 schematically illustrates the proposed framework, comprising three major layers: data input, processing, and decision support.

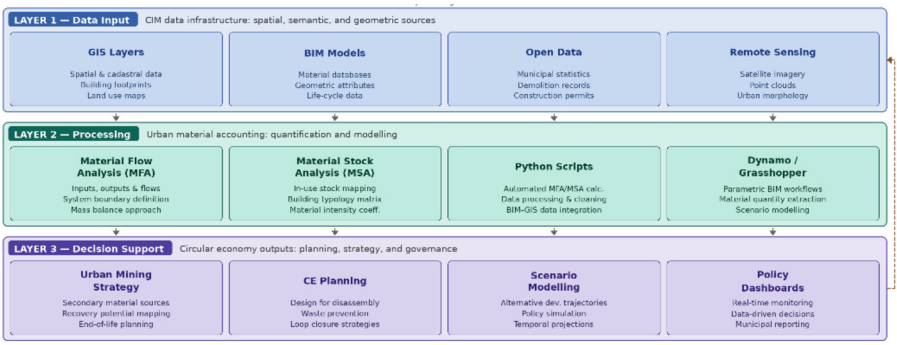


Fig. 1. Schematic diagram of the three-layer CIM-MFA/MSA framework: data input, processing, and decision-support output layers.

MFA requires a systematic quantification of material inputs, outputs, and internal flows within a spatially and temporally defined system boundary. CIM's capacity to integrate multi-scale, georeferenced urban datasets makes it a suitable infrastructure for populating these requirements. At the urban scale, GIS layers provide data on land use, building footprints, infrastructure networks, and administrative boundaries, enabling the outlining of system boundaries and the classification of material flow categories. At the building scale, BIM models contribute semantic and geometric attributes, including material specifications, quantities, and life-cycle data, that can be aggregated to calculate flows entering and leaving the urban system. Together, these CIM components allow for

a spatially explicit MFA that captures not only total material volumes but also their geographic distribution across urban districts or functional zones. Furthermore, CIM's temporal dimension enables tracking flow dynamics over time, supporting longitudinal analyses and monitoring policy interventions.

MSA focuses on identifying and quantifying materials retained within the built environment over extended periods. CIM supports this task by providing a comprehensive, spatially referenced inventory of the urban building stock, combining the geometric resolution of BIM with the territorial coverage of GIS. Building typologies derived from GIS-based cadastral data can be cross-referenced with material-intensity coefficients, typically sourced from BIM models or standardized databases, to estimate the total stock of construction materials embedded in the urban fabric. A key advantage of a CIM-based MSA is its dynamic updateability: as demolition permits, renovation records, and new construction data are incorporated, the stock model can be revised continuously, enabling near-real-time monitoring of material availability and waste generation potential. This dynamic capacity is essential for identifying urban mining opportunities and anticipating future secondary material flows.

The analytical outputs generated by the CIM–MFA/MSA framework can directly inform CE strategies at the urban scale. Material flow data can support waste prevention planning and the design of reverse logistics systems, while stock data can identify concentrations of recoverable materials suited to urban mining initiatives or design-for-disassembly policies. By georeferencing these outputs within the CIM environment, municipalities and urban planners gain access to spatially specific, evidence-based tools to prioritize circular interventions across different districts or building groups. Beyond static reporting, the framework opens the possibility for scenario modeling, simulating the material consequences of alternative urban development trajectories, and for near-real-time policy feedback through integrated dashboards. This positions CIM not merely as a data repository but as an active instrument for data-driven decision-making in circular urban governance, consistent with the broader digitalization agenda of the EU twin transition.

5 Discussion

The proposed framework advances the theoretical understanding of how digitalization can augment the analytical capacity of established urban metabolism methodologies. A persistent limitation of MFA and MSA has been their dependence on fragmented, manually compiled datasets, which constrain both the spatial resolution and the temporal dynamics of the resulting analyses. By conceptualizing CIM as an integrative data infrastructure that combines the territorial coverage of GIS with the semantic and material-level detail of BIM, the framework directly addresses this limitation. Rather than replacing MFA and MSA, CIM improves them from static, resource-intensive assessments to spatially explicit and dynamically updatable analytical tools. This repositioning is theoretically significant: it suggests that the methodological future of urban material analysis lies not in refining the accounting methods themselves, but in strengthening the data infrastructure that feeds them.

The framework can also help address the terminological and conceptual gap identified in the literature. As the review demonstrated, BIM–GIS integration already mirrors

CIM logic in several existing studies; however, the theoretical coherence that a CIM framework provides is absent. By formalizing this integration under the CIM concept and mapping it against MFA and MSA requirements, this paper provides a conceptual foundation that is currently lacking, and that future empirical work can build upon.

From a practical point of view, the framework offers guidance for municipalities, urban planners, and policymakers seeking to operationalize digital tools for circular urban management. The decision-support output layer, encompassing scenario modeling, urban mining strategies, and policy dashboards, translates analytical outputs into the spatially referenced, evidence-based information that urban governance increasingly demands. Crucially, the framework's design principles of interoperability, scalability, and transparency align with the broader European digitalization agenda, making it compatible with existing urban data platforms and municipal planning workflows. By enabling data-driven decision-making on material stocks and flows, the framework supports the shift from reactive waste management toward proactive circular urban planning.

Nevertheless, several limitations must be acknowledged. First, data availability and standardization remain significant barriers: while IFC and CityGML provide established exchange formats, interoperability between BIM and GIS platforms is still partial in practice, and the quality of available data varies considerably across urban contexts. Second, data accessibility, legalization, and lack of knowledge are the main constraints at the institutional level. Institutional capacity poses a challenge as many municipalities lack the technical expertise and infrastructure required to construct and maintain a CIM environment at the scale envisioned by this framework. Furthermore, data privacy and security can pose obstacles to CIM implementation and adoption, as they involve ethical, ownership, and regulatory issues. Third, and most importantly, the framework presented here is conceptual. Its propositions are grounded in the literature and informed by documented BIM–GIS synergies, but they have not yet been subjected to empirical validation. Claims regarding feasibility, accuracy, and scalability remain to be tested through practical implementation. Future research should prioritize case study applications that can cross-check the framework's assumptions against real urban datasets, refine its methodological components, and assess the practical conditions under which CIM-based material analysis can be meaningfully integrated into circular urban planning processes.

6 Conclusions

Building on a prior critical literature review, this study proposed a three-layer conceptual framework that positions CIM as an integrative data infrastructure for urban material analysis, structured into data input, processing, and decision-support output layers. Guided by the BIM–GIS synergies already demonstrated in the literature, the framework proposes an integration logic that existing studies implicitly adopt but have not yet theorized.

The framework aims to make two principal contributions. Theoretically, it provides a conceptual foundation for understanding how digitalization can strengthen the analytical capacity of MFA and MSA, transforming them from static, data-intensive exercises into spatially explicit and dynamically updatable tools for circular urban planning. Practically,

it offers a structured approach for municipalities and urban planners seeking to leverage digital tools for evidence-based resource management and circular economy decision-making, aligned with broader European digitalization and sustainability agendas.

As a conceptual contribution, the framework requires empirical validation before operational conclusions can be drawn. Future research should focus on implementing and testing the framework through case study applications, assessing its feasibility and accuracy against real urban datasets, and developing the data standards and interoperability protocols necessary for broader replication across diverse urban contexts. Ultimately, this study contributes to a growing body of work aimed at building more transparent, adaptive, and circular cities, in which digital tools and material intelligence work to support the transition toward sustainable urban futures.

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Converting Cold Attics – A Scalable Strategy for More Sustainable Cities

Elia Archesso(✉)

Lund University, Lund 223 62, Sweden
el3645ar-s@student.lu.se

Abstract. Cold attics are a widespread feature of the Swedish residential building stock and are known for their structural vulnerabilities. In older buildings, these spaces often represent one of the most problematic envelope components, being associated with significant heat losses and moisture-related issues such as mould growth. These problems compromise the durability, energy performance and safety of the whole building. Among possible interventions, converting attics into habitable spaces offers a combined approach, delivering technical and environmental benefits at both building and city scale by reinforcing urban compactness and locating new housing where services already exist. This study examines the conversion of cold attics into residential units in three properties in Malmö, analysing architectural, energy and environmental implications. After the conversion, all buildings improved their energy class by at least one level. Daylight conditions were assessed using different design strategies to maximise the daylight potential provided by roof exposure. The environmental assessment focused on embodied impacts, comparing attic conversions with average values for new residential construction in Sweden. The converted attics show substantially lower embodied emissions per square metre, demonstrating that reusing existing structures is far more sustainable than building new housing. Finally, the study highlights effects beyond the scale of the single building: attic conversion avoids land consumption, makes use of existing infrastructure, increases housing supply in well-connected areas at low cost and supports urban densification strategies. The results show that this approach can be applied at large scale and contribute to more sustainable buildings, neighbourhoods and cities

Keywords: Cold attic · Sustainable cities · Building energy · Conversion · Daylighting

1 Introduction

1.1 Cold Attics

Cold attics are known to be prone to mould and moisture problems due to the low ventilation rate and the uncontrolled humidity levels of these spaces, which can lead to the downgrade and potential rotting of wood structural elements [1]. Cold attics can also have an important impact on the energy use of the whole building. For example, if

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the floor beneath them is not thermally insulated, cold attics can act as "heat sponges" that absorb all the heating energy that rises from the lower spaces, increasing the energy needed for apartments right under it [2].

1.2 Project Aim

Different solutions for tackling the moisture and energy problems mentioned above have already been explored, the most famous being insulating the attic space to lower the heat losses through the attic. This solution is effective for its purpose, as Hamid et al. [2] already assessed. However, a conversion of cold attics into apartments would not only improve the building's energy performance but also contribute to reducing the housing crisis without having the same impact on the environment as constructing a new building. Cold attic conversion would also help to preserve the green areas on the outskirts of cities and at the same time improve the efficiency of existing buildings as programmed by the "Renovation Wave" [3].

The aim of this research, therefore, is to study the conversion of cold attics into apartments for three different properties located in Malmö for a total of five multi-family apartment buildings. Each building is either part of a complex of similar buildings or representative of a common construction style used for other residential structures of that period. This choice helps to demonstrate the large-scale applicability of this solution for the rest of the city and potentially the rest of Sweden. For each renovated attic, the annual energy use and the environmental impact per square meter of gross area are the main results that will be presented. A comparison of the environmental impact will also be presented between the conversion of the five attics and the average impact of a new residential building in Sweden. Finally, the potential social and economic impact of these conversions is discussed.

2 Methods

2.1 Case Studies

The research focused on the central area of Malmö, chosen for two main reasons: the higher availability of suitable attics in older neighbourhoods (such as Rörsjöstaden, where buildings date back to 1870), and the proximity to the city centre, which guarantees better access to public transport, shops and social services for future residents. Three properties were selected, differing in construction period and typology, to demonstrate the applicability of the conversion strategy across a representative portion of the existing building stock. The proposed designs feature a total of 48 new apartments with an average size of 32.64 m^2.

Property A (Kungsgatan 24, 1902) features a double-sloped roof with a peak interior height of 4.0 m. The main intervention consisted of replacing the shallower courtyard-facing slope with a new insulated shed roof, preserving the street elevation character and yielding 10 new apartments. Daylighting is provided through skylights and new vertical windows on the courtyard wall.

Property B (Sofierogatan, 1943) comprises three Functionalist buildings (B1, B2, B3) sharing the same structural design. All three attics offer a peak height of 3.95 m,

allowing conversion without modifying the main roof structure. Terraces are created on the west-facing side, while skylights serve the east-facing zones, yielding a total of 36 new apartments across the three buildings.

Property C (Torekovsgatan 2, 1946) is the most constrained case, with a peak height of 3.15 m. The renovation includes extending existing façade insulation to all uninsulated walls and relies exclusively on skylights for daylighting, yielding 6 new apartments. A summary of the key characteristics of each case study is provided in Table 1.

Table 1. Summary of case study characteristics.

Property	Year	Style	Attic peak height [m]	New apartments	Apt. size range [m^2]	Daylight strategy
A	1902	Jugend	4.0	10	32–35	Skylights + vertical windows
B1	1943	Functionalism	3.95	12	29–35	Skylights + terraces
B2	1943	Functionalism	3.95	12	28–35	Skylights + terraces
B3	1943	Functionalism	3.95	12	27–35	Skylights + terraces
C	1946	Låga lamellhus	3.15	6	33–35	Skylights only

All glazing elements share the same thermal and optical properties across the three properties: skylights use a high-performance unit ($U_w = 0.92$ W/m^2K, $g = 47\%$), vertical windows a triple krypton unit ($U_w = 0.90$ W/m^2K, $g = 22\%$), and all glazing is equipped with automated interior fabric shading activated when direct solar radiation exceeds 250 W/m^2.

2.2 Buildings Analysis

Energy simulations were performed with ClimateStudio following Boverket regulation [3]. Each building was first simulated in its current state to establish a base energy use, validated against energy declarations and steady-state calculations. Where detailed construction information was unavailable, assemblies were assumed according to Björk et al. [4] based on building type and period. Ventilation flow was set per SS-EN 16798-1:2019 [5], with an envelope infiltration rate of 0.03 $m^3/(s{\cdot}m^2)$ for the renovated scenario versus 0.10 $m^3/(s{\cdot}m^2)$ for the base case, and mechanical ventilation at 35 l/s per apartment. Internal gains, heating setpoint and occupancy were set according to Boverket guidelines.

The main envelope improvement in all cases was roof insulation: 235 mm of glass wool with a new vapour barrier and gypsum board finish, resulting in a roof U-value

of 0.12 W/m^{2}K. The Primary Energy Number (EPpet) — the indicator used to assign energy classes in Sweden — was calculated for both the base case and the renovated scenario using the inputs in Table 2. For Property A, where heating is supplied by a mix of district heating and a ground source heat pump, the full demand was conservatively attributed to district heating for simulation purposes, while correct values were used for DHW COP and weighting factor. U-values for all new envelope elements are summarised in Table 3.

Table 2. Input used for the EP_{pet} calculation based on the heating system used.

Heating system	Heating COP [−]	F_{geo} [−]	Airing losses [kWh/m^2]	DHW circulation losses [kWh/m^2]	VF [−]	DHW COP [−]
District heating	1.0	0.8	4.0	5.0	0.7	1.0
GSHP	1.0	0.8	4.0	5.0	1.8	2.5

Table 3. U-values in W/m^{2}K for the renovated scenario for the renovate attic of the three case studies.

Element	Property A	Property B	Property C
Existing exterior wall	1.88	2.10	0.34
Roof	0.12	0.12	0.12
Partition wall – apartment divisor	0.15	0.15	0.15
Partition wall – room divisor	0.44	0.44	0.44
Slab	0.93	0.93	0.93
Ground slab	3.20	3.20	3.20
Ground wall	3.39	3.39	3.39
Skylight	0.50	0.50	0.50
New added window	0.57	0.57	–
New exterior wall	0.15	0.15	–

Thermal comfort was assessed by counting the annual hours with operative temperature above 26 °C, with a limit of 80 h following BELOK guidelines [7] — the most restrictive among the Swedish and Danish references consulted [6]. Comfort was achieved through passive measures only: automated shading and natural ventilation, without mechanical cooling.

Three daylighting metrics were simulated for each dwelling: Daylight Factor (DF, minimum 1% per BBR [8]), Useful Daylight Illuminance (UDI, 100–2000 lux range,

8:00–18:00 schedule [9]), and Spatial Daylight Autonomy (sDA300/50%, threshold 55% of area per LEED [10]). The shading activation schedule from the thermal comfort simulation was applied consistently across all daylighting calculations.

Environmental impacts were calculated using Boverket's climate database [11], covering stages A1–A5.1 (Global Warming Potential). The GWP per m^2 was determined for each new envelope element and summed across all case studies. Results were compared to the mean embodied impact of new Swedish apartment construction (310 kgCO2e/m^2 BTA) from Malmqvist et al. [12]. As Boverket's database applies a conservative 25% factor to all material impacts, using product-specific EPDs could further reduce the calculated values.

To simplify the study complexity, the same construction sets were applied across all three cases for the new elements, except for the façade. The façade of Property C was made uniform by extending the existing mineral wool insulation to the remaining uninsulated walls. For Properties A and B, the original exterior walls were retained, and a new insulated wood stud wall was added only where structurally required: as the supporting structure for the new roof slope in Property A, and as the enclosure for the new terraces in Property B. Where terraces were constructed, an additional XPS insulation layer was placed on top of the existing slab to ensure thermal insulation and waterproofing for the apartments below. The U-values of all new envelope elements are summarized in Table 3. As the focus of the study was the effect on the energy performance of the overall building, the structural integrity of the proposed interventions was not analyzed in detail and would require additional verification.

3 Results

The attic renovation brought similar changes on the heating demand of all the three case studies. The overall heating demand of each building increased by a maximum of 3% after the different attic renovations. At the same time, the heating energy use intensity (heating energy use per square metre of floor area) of all the buildings decreased between 16% and 18%. Thanks to the additional insulation, property C had a reduction of 51% for the heating demand of the whole building and of 63% for the heating energy use intensity. The Primary Energy Number (EP_{pet}), of each property also saw important improvements. Each building after the attic renovation saw a promotion to a higher energy class. As for the heating demand, property C had a more substantial improvement from class E to class C (Table 4).

The thermal comfort of each apartment was verified in all the new apartments considering the shading system and natural ventilation, keeping the number of hours with an operative temperature over 26 °C under the set limit of 80 h.

The daylight performances of the renovated apartments show the high effectiveness of skylights in daylighting applications to reduce the energy demand for electric lighting. All the renovated attics of the three properties have a mean DF well above the required 1%. The renovated attics perform great also in terms of daylighting where between the three cases the lowest percentage of time with a useful illuminance is 53.10%. Although this result can be partially assumed from the UDI performance, the $sDA_{300/50\%}$ of each new attic is particularly excellent with more than three quarters of the attic's area meeting the 300-lux requirement for at least 50% of the time.

Table 4. Primary energy number and energy class change after the attic renovation.

Case study	Energy Class		EP_{pet} [kWh/m^2/yr]	
	Before	After	Before	After
Property A	F	E	139	125
Property B1	F	E	138	123
Property B2	F	E	140	126
Property B3	F	E	148	132
Property C	E	C	116	65

The last results presented are the environmental impacts of the newly renovated attics. Figure 1 shows the effectiveness of cold attic renovations, comparing impacts of such renovations with the average impact of a new apartment building.

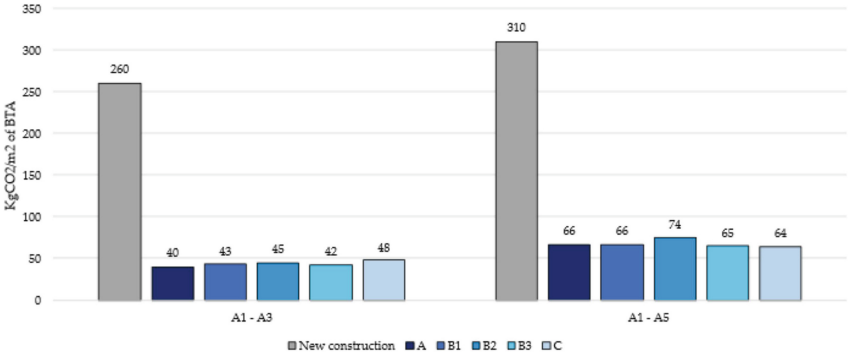


Fig. 1. Environmental impact comparison between a new construction and the different renovated attics per m^2 of BTA.

4 Discussion

Looking at the presented results, a first reflection on the energy performances of the chosen buildings before and after the renovation can be made. The renovation of cold attics solves one of the problems mentioned in the introduction, which is the heat loss through these spaces. If we look at the variation in heat demands across all buildings, it becomes clear that renovating attics can help decrease the heat demands of the original buildings. Even though the reduction is not significant, the savings on the heating energy are almost equal to the heating demand of the new spaces.

Another more intuitive way of understanding the impact of the renovations is looking at energy class improvements, which was the desired result but not taken for granted before the calculations. In this study, all the buildings, which before the renovations were all starting from class F, already fulfilled the energy class requirements [13] for 2033 eight years in advance thanks to the attic renovations. In particular, the conversion of property C is also an example that demonstrate how pairing this renovation with an energy efficiency improvement can help on achieving a zero-emission building stock by 2050.

The reasons on why attics should be converted into apartments are not only backed by the consequent energy improvements, but also by the impressive low environmental impact when compared to the construction of a new building. The results presented clearly show that renovating attics is a valid strategy to reduce the emissions caused of the residential building sector when compared to the environmental impact of new constructions. The choice of the materials used is also a crucial factor in the estimation of the environmental impact of the conversion. As specified previously, the impact calculated in this study used generic data provided by Boverket database which always includes a supplemental conservative factor of 25% on the impact of each material. Using product-specific EPDs could reduce noticeably the impact of the conversions studied by opting for less environmentally impactful products such as bio-based insulation materials or glazing made from recycled materials.

Another important benefit of converting cold attics is also the social life quality of the new apartments. While it is true that the urban expansions bring positive changes in the cities for example creating new infrastructures (such as the new Tram line built in Lund as part of the city's expansion project of Brunnshög), it is also true that new residential constructions would then be placed far from the city center, becoming an issue for the new residents. Previous studies already demonstrated this issue, showing how the uncontrolled and unplanned urban sprawl relates to the raise of social inequalities in terms of access to employment opportunities, public services and urban amenities [14]. As the opposition to this expansionist trend, attic conversion would contribute at achieving the "15-min city" concept that aims creating self-sufficient neighborhoods.

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Automated Detection and Quantification of Building Transformations in the UK

Rebanth Kanner(✉), Danielle Densley Tingley, Martin Mayfield-Tulip, and Ahsan Khan

The University of Sheffield, Sheffield S10 2TN, UK
rkanner1@sheffield.ac.uk

Abstract. Urban areas evolve through continual construction, extension, and demolition, but most monitoring approaches still deliver limited or infrequent information. Although deep-learning techniques have advanced building-change detection, they tend to focus on identifying change rather than measuring its magnitude. In contrast to countries with centralised building registers, the United Kingdom lacks a unified, open-access source of development data, leaving only fragmented local datasets. Consequently, high resolution aerial imagery offers the most consistent and scalable basis for capturing temporal changes nationwide. This study addresses these gaps by creating an automated and scalable pipeline that enables the detection and quantification of building transformations. These transformations include estimates of footprint area change to assess (re)development intensity. The process uses high resolution time-series aerial photographs from EDINA Digimap, which offers consistent, orthorectified imagery across the UK at spatial resolutions up to 12.5 cm. The study makes use of the existing HD-Net architecture, which employs feature decoupling and multi-scale deep supervision to produce precise, high-resolution footprint masks. Once the binary footprint masks are generated, they are analyzed for temporal differences, enabling the identification and quantification of new construction and demolition events. Results highlight the change in building stock in Sheffield between 2012 to 2021 identifying and quantifying building transformation events in terms of change in footprint area. This enables forecasting of secondary resource flows for reuse and more efficient lifecycle response. Information regarding extension and new construction could also help estimate material demand, and the difference between them can help decide future circularity strategies

Keywords: Buildings · Change detection · Deep learning · Circularity

1 Introduction

Urban areas are dynamic systems shaped by continuous cycles of construction, expansion, and demolition. Understanding how the built environment evolves over time is essential for urban planning, infrastructure provision, sustainability assessment, and resource management. However, systematic monitoring of building stock change remains challenging. Conventional approaches rely on cadastral updates, surveys, or

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administrative records that are often incomplete, inconsistent, or infrequently updated [1]. In many countries, the absence of a unified, open-access national building register further limits the ability to track development patterns at scale, leaving researchers and policy-makers dependent on fragmented local datasets.

Advances in remote sensing and deep learning have created new opportunities for automated urban monitoring. High-resolution aerial imagery, collected regularly and consistently across large areas, provides a reliable foundation for detecting physical changes in the built environment. Recent deep-learning models [2–4] have demonstrated strong performance in building extraction and change detection tasks, yet most studies focus on identifying whether change has occurred rather than quantifying its magnitude. Knowledge of this information in turn supports the prediction of secondary material flows for reuse and more effective lifecycle planning. Building change detection can directly support urban mining and material flow planning by identifying where demolition and new construction are occurring, enabling estimation of secondary material availability and primary material demand. It can also inform adaptive reuse and circular construction strategies by distinguishing between redevelopment, extension, and expansion patterns, helping policymakers prioritize refurbishment over replacement and reduce waste generation.

2 State of the Art

Remote sensing based urban monitoring has increasingly shifted from traditional rule based image analysis to deep learning methods capable of automatically learning complex patterns from high resolution imagery [2]. Early approaches based on manually crafted features struggled to generalize across varying urban forms and imaging conditions, while convolutional neural networks (CNNs) enabled substantial improvements in building footprint extraction. More recent work explores models that better capture spatial complexity, such as LDFormer [3], a hybrid CNN–Transformer framework that integrates local features with global attention to improve segmentation accuracy in complex urban scenes.

Another major research direction addresses the influence of image resolution and scale on extraction performance. The Super-Resolution Fusion [4] approach combines the Enhanced Deep Residual Networks for Single Image Super-Resolution [5] with the HyperSeg [6] segmentation model to enhance spatial detail before classification, improving the detection of small or densely packed buildings. Similarly, Multiresolution

Analysis Transfer Learning [7] applies wavelet decomposition to train models sequentially from low to high resolution representations, enabling the learning of scale invariant features while reducing training time. In parallel, research has considered computational efficiency for large-area monitoring. The Edge-Aware YOLO-v8 [8] framework adapts a real-time instance segmentation model by incorporating multi-scale feature pyramids, a Triple Feature Encoder, and explicit boundary extraction using a Prewitt operator, achieving faster inference while reducing noise and jagged building outlines. Collectively, these studies illustrate a broader movement toward specialized deep learning pipelines that balance accuracy, scalability, and operational feasibility for urban analysis.

Within this progression, HD-Net [9] (High-Resolution Decoupled Network) represents a targeted advancement focused specifically on precise boundary delineation, a critical requirement for measuring the change in the footprint of the building. Built on the HRNet [10] backbone, HD-Net introduces a Feature Decoupling–Recoupling module that separates building body features from boundary features before recombining them to produce sharp, high-resolution masks. This design directly addresses the blurred edges commonly produced by conventional CNN segmentation models and achieves state-of-the-art performance with relatively low parameter complexity. Because quantifying urban development requires consistent and geometrically precise footprints across time to reliably estimate changes in area, HD-Net is particularly well suited to multi-temporal analysis of construction, extension, and demolition. Its emphasis on boundary accuracy and computational efficiency therefore makes it an appropriate methodological foundation for detecting and quantifying building transformations from high-resolution aerial imagery in the present study.

3 Study Area

The study area is the city of Sheffield, United Kingdom, which serves as a representative urban case study for analysing building transformation processes. The objective is to quantify changes in building footprint area between 2012 and 2021, distinguishing between new construction and demolition.

The analysis uses high-resolution time-series aerial imagery from EDINA Digimap, providing consistent, orthorectified coverage at spatial resolutions of 25 cm. These data enable the extraction of detailed building footprint masks across multiple time points. Ordnance Survey National Geographic Database (OS NGD) building data are used as ground truth to verify detected footprint changes, providing authoritative spatial information on building extents and attributes for independent validation of the magnitude and type of observed transformations.

It should be noted that some of the aerial images, particularly the older set, exhibit imperfect orthorectification, particularly around tall buildings, which can introduce geometric distortions and lead to errors in measured footprints. The long temporal gap between image acquisitions (nine years) may also result in slight misalignment between datasets, affecting change detection accuracy. In addition, imagery captured at different times uses varying sensors and lighting conditions, producing differences in exposure, hue, and saturation that can influence model performance and footprint extraction consistency. However, steps have been taken to reduce the effects of these discrepancies in the imagery

Although OS NGD data provide an authoritative reference, they may include temporal update delays and representation differences compared to image-derived footprints. Where discrepancies were identified, the footprints were manually corrected or redrawn to ensure closer alignment with the observed building extents at each time point. These combined factors introduce uncertainty that must be considered when interpreting measured building transformations.

4 Methodology

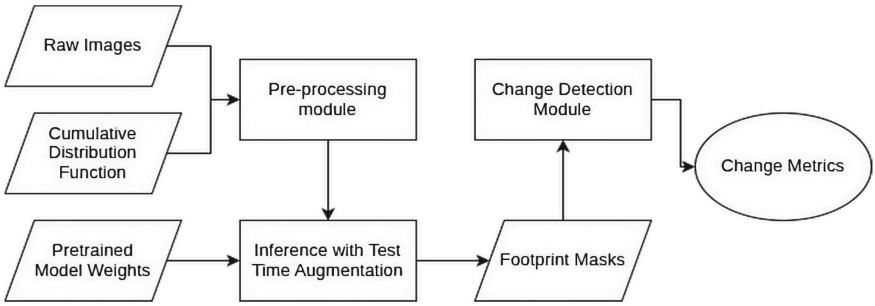


Fig. 1: General Methodology

Figure 1 shows the general workflow of the proposed pipeline. The images are first normalized to an optimized cumulative distribution function(CDF) by matching their intensity distributions. This is to adjust differences in hues and saturations, which can otherwise degrade footprint inference. The normalized images are then input to the HD-Net model [9], where inference is performed using additional test-time augmentation (TTA), and the results are aggregated to further increase robustness. The outputted masks then pass through a rule-based change detection module, which polygonises the footprints and matches paired polygons using overlap, area, and centroid proximity. Identified matches are ignored and the construction and demolition metrics(footprint areas) are calculated from the remaining polygons.

For evaluation purposes, a dataset of 80 tile pairs was compiled across four cities, each pair separated by at least a nine-year interval. Each tile consists of a 1 km^2 raw aerial image and a corresponding 1 km^2 ground-truth building footprint derived from historic OS NGD building data. This dataset was used for hyperparameter analysis to determine the optimal CDF reference and parameter settings for the footprint extraction and change detection modules.

5 Results and Analysis

5.1 Footprint Extraction

The results of footprint extraction on the evaluation dataset are presented in Table 1. Precision measures the correctness of positive predictions (i.e., when a pixel is predicted as a building, whether it is actually a building), while recall measures the proportion of actual building pixels that are successfully detected. The F1 score provides a combined metric that balances precision and recall while accuracy reflects overall classification performance, taking into account both building and non-building pixels.

Overall, the results, visualised in Fig. 2, indicate strong and consistent performance throughout the test set, as reflected by high F1 and precision scores. However, factors such as imperfect orthorectification, spatial misalignment between the images and OS footprints, along with other inaccuracies in the OS footprints, may have introduced

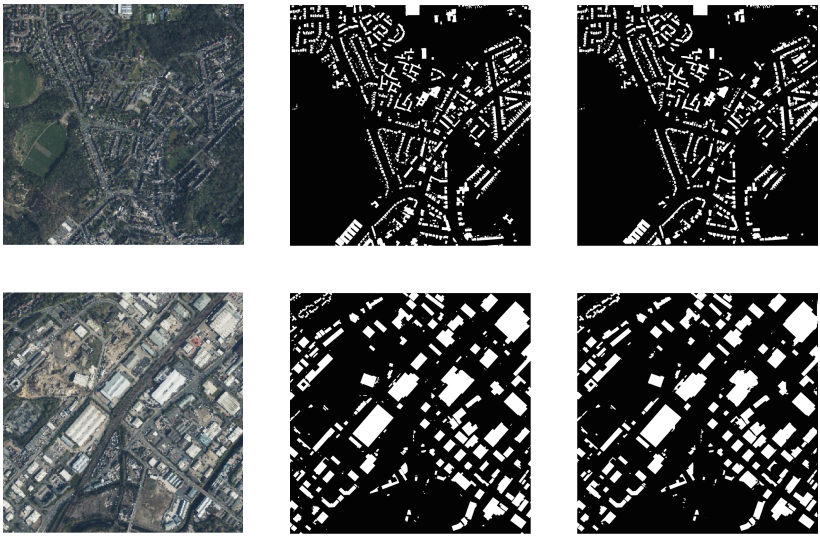


Fig. 2: Comparison of example raw images, ground truth masks, and predicted masks for two sample tiles.

errors affecting performance. Even so, qualitative inspection suggests that applying the identified corrections to the ground truth data of the evaluation dataset would likely lead to further improvements in the reported results.

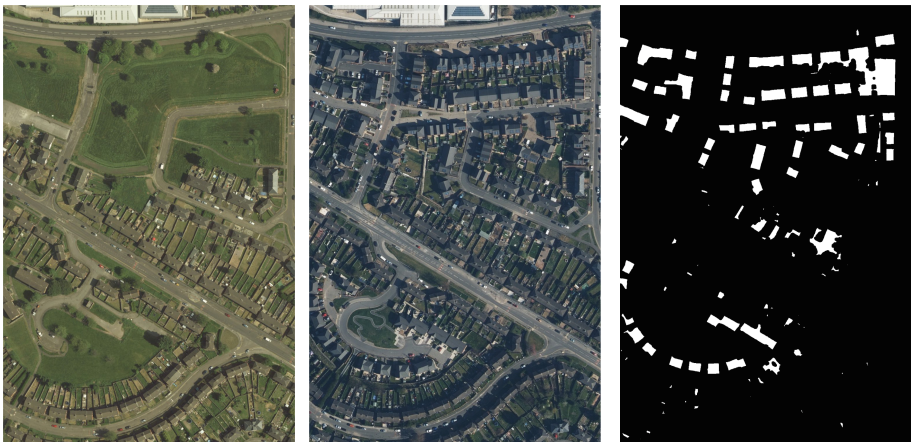
Table 1: Per-city test metrics.

Dataset	F1	Precision	Recall	Accuracy
Birmingham 2013	85.79%	83.41%	88.30%	92.79%
Birmingham 2022	88.75%	88.90%	88.61%	94.54%
Bristol 2014	87.15%	83.82%	90.77%	93.10%
Bristol 2023	88.03%	85.35%	90.89%	93.54%
Manchester 2009	84.54%	85.56%	83.55%	93.37%
Manchester 2023	87.50%	90.68%	84.54%	94.33%
Sheffield 2012	85.36%	83.79%	86.98%	94.35%
Sheffield 2021	88.31%	88.86%	87.76%	95.42%

5.2 Change Detection

Performance varied substantially between cities, with the lowest overall error observed in Sheffield, followed by Manchester, while Birmingham showed notably higher error. Construction estimates were highly accurate in Sheffield and Manchester, indicating

strong detection of new development, while Birmingham exhibited large overestimation in both demolition and construction, leading to poorer net change estimates. From additional manual inspection it appears the change detection module performs particularly well when identifying greenfield construction, as can be seen in Fig. 3, but requires further improvement in other scenarios particularly in demolitions and in dense urban environments. This error is likely partly due to inter-year image misalignment and radiometric differences, which introduce footprint inconsistencies into the rule-based change detection.



(a) Sheffield 2012 **(b)** Sheffield 2021 **(c)** Identified New Construction

Fig. 3: New construction identified by the change module.

Table 2: Change detection errors for selected city pairs (area in m^2).

City Pair	Demo Error (m^2)	Cons Error (m^2)	Net Error (m^2)
Birmingham	+29,900 (+51.6%)	+27,662 (+60.6%)	−2,238 (−18.2%)
Sheffield	+11,319 (+40.2%)	−42 (−0.1%)	−11,360 (−32.9%)
Manchester	+11,749 (+16.2%)	−4,039 (−3.7%)	−15,789 (−41.5%)

5.3 Sheffield Study

Across the Sheffield study area, a total of 402 paired tiles were analysed to quantify building transformation between 2012 and 2021. Using a pixel area conversion of 0.0625 m^2(since each pixel is 0.25 m × 0.25 m), the change detection module identified approximately 1.30 million m^2 of demolition and 2.84 million m^2 of new construction. This corresponds to a net increase of about 1.54 million m^2 in building footprint area over the study period, indicating substantial expansion of the built environment. These

totals however should be interpreted alongside the Sheffield error estimates in Table 2. The near-zero construction error reported for Sheffield suggests that the estimated construction area (2.84 million m^2) is broadly consistent with the reference data at city scale, whereas the positive demolition error indicates that demolition is likely being overestimated. This implies that the true net increase in footprint area between 2012 and 2021 is likely larger than the reported 1.54 million m^2, since an inflated demolition estimate reduces the net change (construction minus demolition). Even with this uncertainty, the results indicate substantial growth in Sheffield's built footprint over the study period, with change dominated by new construction rather than demolition-led redevelopment.

6 Conclusions and Further Work

This study developed an automated pipeline combining a module for radiometric normalization using histogram matching, the HD-Net architecture for high-precision footprint extraction, and test-time augmentation (TTA) to improve inference robustness. The footprint extraction component performed reliably across the test dataset, demonstrating the effectiveness of the integrated pipeline for producing consistent building masks from multi-temporal aerial imagery.

In contrast, the change detection module exhibited lower reliability, particularly in dense urban environments and demolition scenarios. The current approach relies solely on binary footprint masks, which limits its ability to distinguish complex transformations such as partial demolition and building extensions. Future work will therefore focus on integrating RGB imagery alongside footprint masks to improve robustness and accuracy, also enabling the identification of more nuanced changes beyond complete construction and demolition events.

Once change detection performance has been improved, linking detected transformations with OS NGD attributes offers significant potential to enrich the analysis. This integration could support the transition from footprint-based change measurement toward estimation of building material stocks and flows, enabling more detailed assessments of resource demand, reuse potential, and circular economy strategies within the built environment.

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Transition Toward Circular Infrastructure Management in Tourism Enterprises: A Latvian Case Study

Sarmite Rozentale(✉), Dace Dance, and Mara Grinberga Silaua

Vidzeme University of Applied Sciences, Valmiera, Latvia
sarmite.rozentale@va.lv

Abstract. Effective infrastructure management plays a crucial role in implementing circular economy (CE) strategies, promoting resource efficiency, reducing waste, and ensuring business viability. This creates a challenge in exploring opportunities for convergence between the environmental and economic dimensions in small tourism businesses. To this end, the Latvian Council of Science funded a study by Vidzeme University of Applied Sciences and the School of Business and Finance of the University of Latvia. Using a Participatory Action Research (PAR) approach, ten small tourism-related enterprises participated in the study, focusing on joint research, action, and understanding to create knowledge together with them and for their benefit. The study involved in-depth interviews, focus group discussions, and financial data analysis. Adopting CE principles in infrastructure management enables tourism enterprises to reduce costs, increase resource efficiency, and minimize waste, which is economically beneficial given the rising cost of resources. It includes designing and constructing infrastructure, adapting outdated infrastructure to new needs, and using water- and energy-saving equipment and technologies for wastewater treatment. Despite the potential benefits, there are also challenges and limitations to transitioning to circular infrastructure management. The initial costs of implementing a CE can be a barrier for many small tourism enterprises. Such an approach includes investments in new infrastructure and technology. Another limiting factor is the low level of awareness and understanding of the principles of the CE. To overcome these obstacles, greater awareness, supportive regulations, and cooperation among all stakeholders are needed

Keywords: Circular Economy · Infrastructure Management · Small Tourism Enterprises

1 Introduction

The circular economy (CE) has become a significant area of research in the tourism industry, given its increasing importance in policymaking, particularly in the European context. Several authors point out that the introduction of CE principles can streamline business processes, reduce costs and resource consumption, and mitigate negative environmental impacts [1, 2]. Furthermore, the integration of such principles promotes the efficiency and sustainability of the sector [3].

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Studies indicate that large companies generally possess the necessary resources, skills, and knowledge to implement CE principles [4]. The pursuit of competitive advantage in global markets has long been a key driver of sustainable and responsible business management. However, small and medium-sized enterprises (SMEs) often face difficulties in consistently implementing the transition to a CE, as they often lack the resources, knowledge, and strategic approach to integrate sustainability into their business practices from a circular perspective. Companies must balance profitability with political and environmental considerations. However, the transition to a CE requires significant financial resources and knowledge, both of which are often limited, especially for SMEs [5].

The study used a participatory action research (PAR) approach, involving ten small tourism businesses. This approach is based on joint research, practical action, and awareness-raising, generating knowledge in collaboration with companies and for their direct benefit.

The research area was, firstly, Gauja National Park, which is the largest and oldest specially protected nature area in Latvia and one of the country's most important tourist destinations; secondly, Valmiera, which is an important administrative, economic, and cultural center of the Vidzeme region; and thirdly, Riga, as the capital of Latvia, which is the country's largest tourist destination. This choice provides a broader context for the analysis of the activities of tourism enterprises, which share common operational challenges - inefficient infrastructure and pronounced seasonality of demand.

This article analyzes the transition to a circular business model in small-sized Latvian tourism companies and organizations, with a particular focus on infrastructure management as a key factor in increasing resource efficiency, reducing waste, and ensuring business sustainability.

2 Theoretical Framework

This section presents the theoretical framework of the analytical perspective used to investigate the infrastructure management of Latvian small-sized tourism enterprises in the context of a CE.

Based on the study's methodological approach, we used the concepts of circular infrastructure management and the circular business model framework as complementary research lenses to examine the current situation of small tourism businesses in Latvia and their potential to transition to more circular management. The theories used in the study were selected for their ability to explain circular-economy-based infrastructure management at the company level.

Recent literature shows a shift from "traditional" infrastructure or facility/asset management toward a lifecycle, data, and flow-based approach, in which infrastructure is viewed not as a linearly consumed resource, but as a set of materials, information, and value that can be managed over the long term [6].

Traditional corporate infrastructure management focuses on facility management, procurement, service specifications, and process structuring [7].

Recent literature has increasingly adopted a CE approach, which shifts the focus of infrastructure management from operations to circular life-cycle management [8, 9].

Digital tools such as Building Information Modelling (BIM), Historic Building Information Modelling (HBIM), Digital Twins (DT), and data platforms enable information to be used in the design, construction, operation, renovation, and demolition of buildings [10].

Another key area is information and knowledge management, emphasizing that digitalization improves the management of information and knowledge, standardizes data structures, and promotes data traceability, storage, usability, and reuse. Infrastructure management is the planning, operation, maintenance, and improvement of infrastructure so that it operates efficiently, safely, and sustainably throughout its life cycle [11, 12].

The implementation of the circularity principle is not possible without appropriate policies, a regulatory framework, and a system of standardization [13].

Although the topic of circularity has developed rapidly, there are also some gaps. First, many studies are conceptual or at the framework level, but there are relatively few empirical studies on how companies integrate circularity into infrastructure management in practice [14]. Second, while there are many indicators and methodologies, there is no single dominant approach that is standardized and easily comparable across companies [15]. Third, the perspective on buildings and construction is well developed, but models for managing internal infrastructure within companies across sectors are less developed [16]. Companies face organizational, financial, and institutional barriers to implementing the CE.

The main principles of circularity applicable to infrastructure are resource efficiency – minimizing resource consumption, for example, energy-efficient buildings, smart heating and lighting systems, and effective water management [17].

3 Methods

To increase the commitment of small tourism businesses to implementing CE practices in infrastructure management, we conducted an action research project in collaboration with 10 Latvian companies in the tourism sector located in areas representing various tourism contexts – protected natural areas, regional tourism centers, and the metropolitan environment. This approach is characteristic of case study methodology, which enables analysis of complex economic phenomena, including the implementation of the CE, across various contexts and situations [18].

According to the Eurostat glossary, tourism encompasses a wide range of sectors in accordance with the European Community's statistical classification of economic activities (NACE Rev. 2) [19]. The organizations involved in the study represented various industry segments, including manor and country estate hotels, event organizers, a state museum reserve, the sports base of the Latvian National Sports Center, the National Zoo, beverage producers that combine production with tourism, and a regional public transport service provider. The study also included regional non-governmental organization's involved in nature conservation and environmental education.

The participatory research process consists of three stages (Fig. 3). The first stage is preparatory, involving the selection of companies through the analysis of publicly available information, such as their websites, social media, annual reports, and industry

policy planning documents. An initial interview is conducted to assess the company's suitability for the study and willingness to participate in action research. This process prepares the company to discuss CE issues and their application in infrastructure management with the researchers. If a participation agreement is reached and the outcome is positive, a contract is signed.

The second stage involves collecting data through in-depth, face-to-face interviews with senior management to gain direct insight into the company's infrastructure and assess its knowledge and experience of the CE. It is followed by defining the data in accordance with the literature, considering the specific sector and nature of the business. The company submits qualitative and quantitative data, including a self-assessment of how CE principles are applied in infrastructure management. This self-assessment includes a CE log documenting specific daily examples in accordance with the 9R framework, adapted from Potting [20].

The third stage involves analysis and implementation. This stage includes evaluating, validating, and cleaning data, as well as assessing the company's current experience with the CE and its potential to transition to a circular-economy approach to infrastructure management. The company's annual report's financial data was also taken into account. Following the procedure, researchers and business representatives collaborate in a joint workshop to identify issues and create solutions.

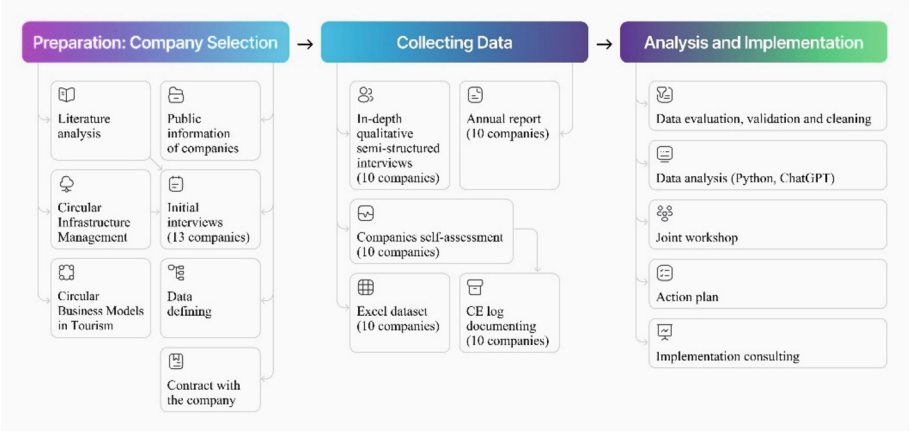


Fig. 3. Research Design

Finally, a plan is developed to transition to a more circular management style. For eight months, researchers and companies worked together on the action research project.

4 Results

The company's core business areas summarize the analysis results. Overall, fixed asset management takes a practical approach to resource conservation, guided by economic logic and experience in daily operations. However, adopting a more systemic approach to the CE requires structured data management, investment planning, and infrastructure optimization. An assessment of the current situation reveals positive practices, such as prioritizing durable equipment, repairing equipment instead of replacing it immediately, leasing or sharing some equipment, and evaluating investments based on return on investment. These practices align with CE principles, such as extending product lifecycles, optimizing resource consumption, and divesting from unnecessary fixed assets.

However, most companies lack a fixed-asset lifecycle management system and do not analyze equipment repair costs, equipment-specific energy consumption, or equipment service life. It means that infrastructure is managed reactively rather than strategically. This situation is particularly characteristic of the management of historic buildings, where technical information is fragmented or not collected. In this context, the implementation of HBIM and DT solutions would provide an opportunity to transition to data-driven and proactive infrastructure management. In the area of energy management, companies are already using several energy-efficiency solutions, such as energy-efficient light bulbs, motion sensors, ventilation timers, thermostats, and automatic heating controls, as well as selecting energy-efficient equipment. Some companies also track energy consumption for individual buildings and equipment, have conducted energy audits, and have installed more modern heating or ventilation systems, such as heat pumps or heat-recovery ventilation systems, which significantly reduce energy consumption. However, in most cases, no energy management system has been established. Table 4 presents the study's results, highlighting the study's areas and their strengths and weaknesses.

Table 4. The participatory research results

Area	Key Strengths	Most Common Weaknesses
Fixed Asset Management	Regular maintenance and repairs, in-house servicing in certain cases, reusing car and equipment parts, renting or sharing equipment, leasing unused space and land, and investing in more energy and water-efficient and environmentally friendly solutions.	A systematic life-cycle analysis of fixed assets is not carried out everywhere. This results in a lack of data on repair costs, service life and optimal replacement times. This limits the ability to assess long-term impacts.
Waste Management	Systematic sorting; sending cardboard, glass, metal, equipment, and parts for recycling; storage of reusable parts; regular waste reports and audits at some companies.	Not all companies have a detailed waste stream analysis; the recycling rate and the total amount of waste generated are not always measured.

(*continued*)

Table 4. (*continued*)

Area	Key Strengths	Most Common Weaknesses
Energy Monitoring and use of Renewable Energy	LED lighting; optimization of heating and ventilation; selection of energy-efficient equipment; consumption monitoring; ISO 50001 or an equivalent energy management approach in some companies; separate metering by building.	The use of renewable energy sources is generally low; not all locations have comprehensive energy data analysis or clear KPIs; not all facilities have modernized infrastructure.
Water Monitoring	Water consumption monitoring at some companies, on-site treatment facilities, wastewater management, and, in certain cases, water metering.	The approach to water circulation is inadequate; there is no technical water reuse, rainwater is rarely used, and comprehensive consumption analysis is not always available.

5 Discussion

Although sustainability has been considered a key factor for long-term growth in infrastructure management for several decades, there is still a significant methodological and empirical problem: it is not sufficiently clear how the principles of sustainable infrastructure management are actually transferred from the research sector to small tourism businesses and what resources and processes are required for this.

Our research, based on the literature on the CE of tourism sources in management processes of the built environment, developed a methodology and took action to support small tourism enterprises transitioning to a CE in infrastructure management. As a result of the study, we developed a roadmap for the transition to better implementation of circular principles in small tourism enterprises (see Table 5).

Table 5. A roadmap for transitioning to more circular infrastructure management.

Main objectives	Planned activities	Expected result/indicators
Create a common understanding and database for CE	• Develop a circular infrastructure management action plan • Conduct a waste audit • Define key resource indicators • Induction training for employees • Implement digital data accounting • Prepare project applications for external funding	Baseline indicators set, action plan approved.
Resource efficiency (energy, water)	• Energy management approach • Pilot projects for water saving (use of rainwater for irrigation, technical needs) • Optimization of energy consumption in historic buildings (automation, sensors, regulation)	Reduced risk of increased operating costs; prepared the basis for larger investments.
Waste prevention and management	• Implement full waste flow accounting (domestic, biological, hazardous) • Expand sorting infrastructure throughout the territory + visitor information	Increased waste diversion rate; less dependence on landfills
Fixed asset management	• Gradually introduce BIM, HBIM, and DT solutions into fixed asset management to ensure data-driven, efficient, and sustainable infrastructure management, but at a minimum, develop a "life cycle plan" for fixed assets (repair, lease, replacement).	Ability to monitor technical condition, energy consumption, and maintenance needs in real time.

(*continued*)

Table 5. (*continued*)

Main objectives	Planned activities	Expected result/indicators
System-level innovations	• Annual evaluation and public reporting of sustainability indicators • Incorporating circular objectives into the strategy	Increasing competitiveness

It is recommended that the resource efficiency and CE indicators defined in the guide are integrated into digital material passports and linked to BIM, HBIM and TD solutions to enable the structured management of lifecycle data for fixed assets.

6 Conclusion

The transition to infrastructure management based on the principles of the CE is hindered by high initial costs, low awareness and the requirement for supportive regulations and collaboration. This presents a particular challenge for businesses in historic buildings, where changes to engineering systems require significant investment, as well as design and coordination. Many traditional sustainability solutions, such as insulation, renewable energy infrastructure, ventilation modernization, and water reuse, are either technically unfeasible or too expensive for the company. This situation clearly demonstrates objective limitations to sustainable, rational decision-making. HBIM and DT solutions can help businesses in the tourism sector to manage historic buildings sustainably and promote the CE. This is particularly important for businesses that manage cultural heritage sites such as castles and manors, where balancing high visitor numbers with building preservation is essential.

In the Baltic States, including Latvia, solutions for the management of cultural heritage in the tourism sector using HBIM and DT are still in the early stages of development. However, Latvia already possesses significant technological and institutional potential in this area. Currently, universities, companies and cultural heritage institutions primarily use laser scanning, photogrammetry, BIM and 3D archiving for documentation and restoration projects. However, integrating these technologies with sensor data and real-time analytics could facilitate the data-driven management of tourism infrastructure.

As small businesses often face financial constraints when transitioning to a CE, sustainability financing should be primarily viewed as a tool for strengthening internal efficiency and competitiveness. Data-driven process improvements, resource monitoring, automation and employee skills development require relatively small investments that can be financed from existing cash flow and deliver quick, measurable returns.

The most effective approach is a phased financing model, starting with small improvements using internal resources, moving on to co-financing and loans, and finally implementing larger investments with EU and national support. This approach reduces financial risk, strengthening business resilience during the transition period while promoting sustainable infrastructure and resource management in the tourism sector.

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Re-evaluating Comfort: A Data-Based Analysis of Latent Transport Poverty in Latvian Urban Mobility

Dita Zemīte(✉) and Māra Grīnberga-Šilaua

Vidzeme University of Applied Sciences, Valmiera, Latvia
dita.zemite@va.lv

Abstract. The European Commission's Action Plan for the European Pillar of Social Rights recognises transport as a basic service and its critical role in promoting social inclusion and ensuring equal opportunities. Furthermore, sustainable transport and mobility are prioritised at both global and regional levels, through policy frameworks and strategic planning tools

The most recent National Travel Survey (NTS) conducted in Latvia shows that around 80% of annual passenger-kilometres in Functional Urban Areas (FUA) are generated by fossil-fuelled private cars. The most recent 2024 assessment of the Transport Development Guidelines for 2021–2027 also reveals that the projected reductions in greenhouse gas emissions have not been achieved, mainly due to the continued reliance on private cars. The previous NTS showed that 38% of respondents cited personal comfort as the main reason for using private cars. This study investigates whether "comfort", which is often identified as the main motivator for car travel, reflects a genuine desire or compensates for shortcomings in public transport systems. In situations of limited availability and accessibility, comfort can serve as an indicator of transport poverty, encompassing its dimensions of accessibility, availability, affordability and adequacy. By conducting statistical and trip-stage analysis of NTS data in Riga FUA, this study identifies patterns of latent transport poverty, in which car dependency may mask underlying inequality and exclusion

The conclusions emphasise the importance of integrating transport poverty reduction strategies into the development of a Sustainable Circular Transport System in transport planning to further promote inclusive and sustainable mobility

Keywords: Transport poverty · People mobility · Travel survey · Circular transport system · Sustainable mobility

1 Introduction

To align national policies with the European Green Deal and related European policy frameworks [1], as well as with the United Nations Sustainable Development Goals No. 11 (Sustainable Cities and Communities) and No. 13 (Climate Action) [2], Latvia needs to transform its transport system to achieve climate neutrality.

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The latest evaluation from 2024 of Latvia's Transport Policy Guidelines indicates that the planned reduction in greenhouse gas (GHG) emissions in the transport sector has not been achieved [3], road transport and private cars undoubtedly impact that, available data from 2023 proves that 97.4% of the total transport GHG are from road transport and 50.5% of those are generated by passenger cars [4]. According to the National Travel Survey (NTS) 2021, the passenger modal split shows that almost 82% passenger-kilometres per year were travelled by private cars [5] in Functional Urban Areas (FUA) [6] of Latvia. In 2025, electric vehicles accounted for around 1% of the total car fleet, while almost 70% of passenger cars were diesel-powered at the beginning of 2025 [7]. Environmental concerns are further exacerbated by the age structure of the vehicle fleet: 76% of cars are over 10 years old, and 26% are over 20 years old [8]. To address the issue of private cars, the Circular Economy (CE), is proposed, a system that aims to reduce waste and recycle resources, and offers a way to move from linear to Circular Transport System (CTS) - which is designed to separate travel from using limited resources - to Sustainable Circular Transport Systems (SCTS) that also consider social fairness and people's well-being [9–12].

This study examines the concept of CTS from the perspective of CE transport service use perspective [13] and analyses that the social dimension of sustainability is not sufficiently reflected in existing concepts. To address this gap, the paper proposes to expand the concept towards SCTS that includes social considerations.

The empirical analysis focuses on travel patterns in the Riga FUA using trip data from the NTS. In particular, the study examines "comfort" if stated by survey respondents as a key factor influencing private car use for the particular trips and assesses the availability of public transport (PT) alternatives in terms of accessibility and travel time. Accessibility is considered as one of the four dimensions of transport poverty and is therefore used to assess the potential of PT as an alternative to private car transport use in Riga FUA.

The findings suggest that the use of private cars in Riga's FUA could be explained less by psychological motivation or status considerations and more by structural factors, such as lack of transport and the limited competitiveness of PT in terms of accessibility and service provision [14–16]. The results contribute to the discussion on structural changes in transport system aimed at improving the competitiveness of PT in the transition to SCTS and achieving mobility justice [17].

2 Literature Review: from Linear to Sustainable Circular Transport Systems

A transportation system consists of infrastructure, vehicles, terminals (networks) that enable the movement of passengers and freight (demand) between locations (nodes) [18]. CTS are socio-technical structures designed to decouple mobility from the consumption of finite resources [19]. Unlike the linear model, CTS employ a closed-loop approach throughout the entire material and energy cycle. This change is mainly explained by Socio-Technical Transition Theory, which suggests that real change occurs only when new technologies align with changes in how people use them, the rules that govern them, and the cultural conversations surrounding them [20]. However, early formulations of CTS often emphasise material efficiency - specifically, the "3R/4R" principles of

industrial ecology (reduce, reuse and recycle/ reduce, reuse, recycle, recover) - while possibly neglecting social considerations and the essential "human" requirements for a resilient network, such as community engagement and equitable access to resources [9, 19, 21, 22].

To address this issue, the concept of SCTS has been developed. The SCTS functions as a comprehensive system that integrates economic efficiency, social responsibility, and behavioural change [23]. This evidence points to a shift from a technical materials science perspective to a comprehensive approach that integrates social justice.

While CTS mainly emphasizes the optimization of resource flows and environmental efficiency, SCTS includes the social dimension of sustainability. Within SCTS, the dimensions of transport poverty – accessibility, availability, affordability and relevance – can be addressed in several ways. First, accessibility can be improved by shifting the focus away from private car use towards widely interconnected multimodal networks and PT systems that meet the diverse needs of users, for instance in densely populated FUAs. Second, accessibility can be improved through urban planning approaches that reduce physical distances to essential services and PT stops, such as compact urban development or concepts such as "superblock" [24]. Third, affordability ensures that mobility services remain financially accessible. Finally, adequacy and accessibility require that transport services are inclusive, equitable and meet the mobility needs of different population groups [12, 25].

Ultimately, SCTS not only optimizes transport operations, but also fundamentally transforms them. By integrating these dimensions into its conceptual framework, SCTS supports the transition to a circular transport system that is not only resource efficient but also socially inclusive.

3 Methodology

The study uses case of Latvia - Northern European country and a member of the European Union since 2004, characterised by a developed but evolving transport network; however, low population density, population decline and budget constraints in reducing regional PT services limit the prospects for sustainable transport and complicate the provision of connectivity without private cars. The total area is 64,589 km^2, the population is 1.9 million according to the latest data in 2025 by Central Statistical Bureau of Latvia, and the population density is 30 inhabitants per km^2 [26], making it one of the least populated countries in the EU. The total length of Latvian transport lines has kept decreasing since 1990 [27].

For this study, a quantitative descriptive comparative approach based on statistical data analysis was used. Descriptive statistics were used to analyse the distribution of travel times for private car and PT trips. Visual inspection of the histograms indicated that the travel time distribution deviated from the normal therefore non-parametric Wilcoxon rank sum test was used. Statistical analyses were performed using the RStudio.

The study uses trip microdata from the NTS 2017 (N = 14011) [28]. The NTS provides nationally representative information on individual daily travel habits, including trip characteristics, mode of transport, trip distance and stated reasons for choosing the mode of transport.

For this study, the dataset was filtered using the following criteria:

– Geographical and temporal scope – Riga FUA and working days.
– Mode of transport – only trips made by private car and driver of the car.
– All purpose trips included, excluding those where the main purpose stated was accompanying persons.
– Main reason for choosing a car for a trip – comfort was selected.

The analysis aimed to assess whether car use motivated by personal comfort that according to the results of the NTS 2017 where 38% of respondents indicated personal comfort as the main reason for choosing a private car [29], could theoretically be replaced by PT and whether such travel behaviour may be indicative of underlying constraints related to the accessibility and availability dimensions of transport poverty. Within this framework, PT mobility options were systematically assessed, travel time and number of transfers were made by selecting two Wednesdays in March 2026, a departure time of 2 PM (when multiple travel options were available, the fastest connection was selected), and publicly available PT schedules on Google Maps. The standardised assumption for this analysis was that available PT and rail routes, as well as schedules, had not changed substantially in 2026 compared to 2017. The analysis focused on the differences in travel time between private cars and PT. The analysis did not include individual-specific constraints that might have influenced the choice of transport mode (e.g. physical limitations, household responsibilities or employer requirements), as such preconditions were not available in the data set. Therefore, the comparison reflects the theoretical substitution potential, not the realised probability of behaviour. The approach enabled assessment of whether the stated reason for "personal comfort" may mask structural mobility constraints and thus reflect latent transport poverty rather than purely preference-based travel behaviour.

The analysis may be subject to survey-year bias, as it relies on data from the NTS 2017; however, it ensures conceptual coherence with the study's aim, assess car trips motivated specifically by personal comfort considerations. In Latvia, the most recent national travel survey was conducted in 2021, however it did not include a specific question on a reason for choosing a private car.

4 Results

When comparing travel times between private cars and PT alternatives, significant differences were observed. The Wilcoxon signed-rank test confirmed that travel times by PT are significantly longer than travel times by car ($V = 0$, $p < 0.001$). The average travel time ratio between PT and car travel was 4.05, indicating that trips by PT would require more than four times the travel time. Only 10.7% of trips could be made by PT in twice the travel time than by car, and only 3.0% of trips in 1.5 times the travel time than by car. Furthermore, 51.7% of trips using PT would exceed the travel time by at least 30 min.

Table 1 presents descriptive statistics on travel times by car and PT for the analysed trips in Riga FUA. The results show significant differences between the two modes of transport. Travel times by PT are significantly longer compared to travel times by car.

The Fig. 1. shows the distribution of private car and PT travel times in the Riga FUA. The results show a clear difference between the two modes of transport. Car travel times are significantly shorter and more uniform, with a lower median and a relatively

Table 1. Descriptive statistics of travel times for cars and PT.

Travel mode	Median (min)	Min (min)	Max (min)	IQR
Car	10	1.3	70	14.15
PT	41	10	218	37

narrow interquartile range. In contrast, PT trips have significantly longer travel times and greater variability. Several extreme values were observed for PT, indicating particularly long travel times, in some cases exceeding 150 min.

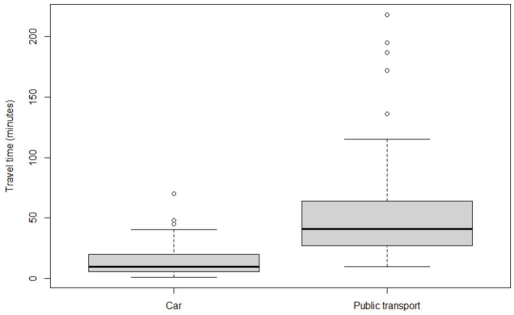


Fig. 1. Distribution of travel times by mode of transport (private car and PT) using box plots in the Riga FUA.

5 Conclusions

The results show a significant travel time disadvantage of PT compared to car travel. Such differences can increase reliance on private cars and limit the competitiveness of PT alternatives. The findings also suggest potential access inequalities in Riga FUA, as people without access to a car may face longer travel times when using PT. Improving the competitiveness and connectivity of PT in terms of travel time could therefore be important to support SCTS development.

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Advancing Circularity in Resource Intensive Public Facilities: A Participatory Action Research of Museums, Zoological Gardens and Sports Facilities

Dace Dance(✉), Mara Grinberga-Silaua, and Sarmite Rozentale

Vidzeme University of Applied Sciences, Valmiera, Latvia
dace.dance@va.lv

Abstract. Public facilities such as museums, zoological gardens, and sports venues, which support community well-being and economic activity, are resource-intensive as they have high demands for materials, energy, water, and generate significant amounts of waste.

Furthermore, because public resources finance them, they are uniquely positioned to serve society through their direct targets and to serve as role models for circularity practices.

This study adopts Participatory Action Research (PAR) to investigate a national museum, a national sports event facility, and a national zoological garden using a multicriteria framework that combines secondary data analysis, stakeholder interviews, and an examination of circularity strategies and practices. The same model has been applied to all participants, with slight adaptations, thereby making the data comparable and the evaluation outcomes more closely aligned with the participants' real operational context.

Data collection is based on a self-evaluation questionnaire, semi-structured interviews, participatory focus groups, field observations, and reflective diaries of circularity practices maintained by participants, with a final evaluation at the end of a one-year study.

Findings reveal each facility's circularity potential, current challenges and barriers. The main challenges for zoological gardens are water management and improving organic waste loops; for sports facilities, it is infrastructure modification and strategies for shared-use resources; for museums, it is maintaining conservation through digitalisation and resource-sharing strategies.

The results demonstrate that circularity practices not only improve nature conservation directly but also strengthen public institutions' resilience and operational efficiency. Being visible through their actions increases public engagement with circularity.

Keywords: Resource Intensive Public Facilities · Circularity Practices · Participatory Action Research

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1 Introduction

Zoos, sports organisations, and museums are prime candidates for circular economy (CE) research because they both consume vast resources and generate substantial waste, and they uniquely influence tourists and local communities. These organisations use large daily quantities of water and energy for infrastructure, visitor services, and facility management, leading to significant amounts of food, packaging, and organic waste. The tourism and cultural sector stands out as a major driver of energy and water consumption and as a notable contributor to CO_2 emissions and waste. Addressing these pressures by implementing CE principles is therefore essential for sustainable development. At the same time, these institutions hold considerable untapped potential for advancing the circular economy [10]. They serve as role models of circular practices for society, such as waste sorting, material reuse, and sustainable infrastructure solutions.

In the circular economy, value creation in public infrastructure management relies heavily on effective asset management, resource circulation, and extending the infrastructure life cycle. Furthermore, because public procurement accounts for a massive portion of the economy, these state and municipal facilities have the power to act as first movers, creating vital demand-side pressure in the market to accelerate the broader transition to a circular economy [12].

Still, there is a gap in understanding the functional reality of *why* they are struggling to implement deep circular practices. The gap lies in the fact that current CE literature focuses on macro-level systemic shifts, and the R framework for CE [5] often overlooks the unique constraints of resource-intensive public institutions in geographically sensitive areas. In addition to recent practical CE studies and developed self-assessment tools tailored for the tourism sector, they focus on private Small and Medium-sized Enterprises (SMEs), such as hotels, restaurants, and wineries [13].

The study addresses this gap by focusing on the operational realities of these facilities through Participatory Action Research (PAR). The objective of the research is to investigate the current circularity potential and the challenges and barriers [8] for resource-intensive public facilities. It seeks to prove that implementing CE practices in resource-intensive public facilities strengthens their operational efficiency.

The transition towards a circular economy (CE) in the built environment is a pressing necessity. Across the globe, the construction sector continues to exert tremendous pressure on natural resources, energy systems, and waste management infrastructures. At the same time, it holds untapped potential for CE [1].

For asset-heavy public facilities, circular value creation relies heavily on maintaining the built environment, extending the lifespan of physical assets, and optimising resource streams to lower operational expenditures (OPEX) [3].

Given these organisations' high resource consumption, the complexity of their infrastructure, and their potential to advance the practical implementation of circular economy principles, the study analysed the integration of circular economy principles into organisational management using a multidimensional approach to data collection and analysis.

2 Methodology

Study uses Participatory Action Research (PAR) to investigate resource-intensive public facilities. This study applies the PAR methodology to analyse the needs and challenges of tourism SMEs in their transition towards the circular economy. PAR is widely used in the tourism sector and in circular economy projects and involves stakeholders in the research process [13].

PAR is highly effective because it directly connects research to real-world actions, enabling researchers and institutional stakeholders to generate practical knowledge collaboratively. Furthermore, applying PAR within a multi-case framework allows researchers to identify shared systemic barriers that interact with unique operational realities and respondents' knowledge [4].

Within the current research, the PAR process consisted of 3 phases. First ("Preparation"), organisations were selected (with limitations set on certain regions and tourism-related sectors according to NACE, and through on-site visits and in-depth interviews to track company readiness and willingness to collaborate). Second ("Data collection"), Excel data sheets were prepared, and organisations collected data on CE practices, including exact data, additional comments, and bi-weekly information in a CE practices diary according to the 9R framework adapted from Potting [11]. Third ("Analysis and Implementation") involved evaluating, validating, and cleaning data, aligning with available public financial reports, and holding a joint workshop with organisation representatives to identify further development potential.

The organisation's CE maturity level was assessed on an ordinal scale: Basic, Growth, and Professional. Basic maturity describes where CE practices are not yet embedded in daily management areas; Growth maturity shows where CE practices are successfully integrated but lack a systematic approach; and Professional maturity describes CE practices that are highly systematic and integrated into both daily operations and long-term strategies. The maturity evaluation was based on combining qualitative and quantitative data collected during the one-year PAR period.

By applying the same model to all participants, the goal is to gather comparable data that reflects the real operational situation and context. As part of a scientific research project (see Acknowledgement), a PAR study was conducted across 10 different organisations. To address the current literature gap, this article focuses on public, resource-intensive facilities; therefore, three specific institutional case studies - a National Museum, a National Zoological Garden, and a National Sports Event Facility, which have been selected for further research.

The study used a mixed-methods approach and data triangulation to assess how circular economy (CE) principles are integrated across management areas. The organisation performed a self-assessment of CE principles in business management areas (see Fig. 1). At the same time, representatives kept structured diaries documenting the timing, context, and rationale of daily activities and decisions aligned with the 9R principles, capturing detailed insights into CE-related actions. We also reviewed financial indicators to assess investment opportunities and potential financial constraints for launching and developing CE initiatives. All data were cross-referenced to compare the organisation's self-reported CE practices with its actual operations and financial capacity. This process improved the reliability and validity of the study's results.

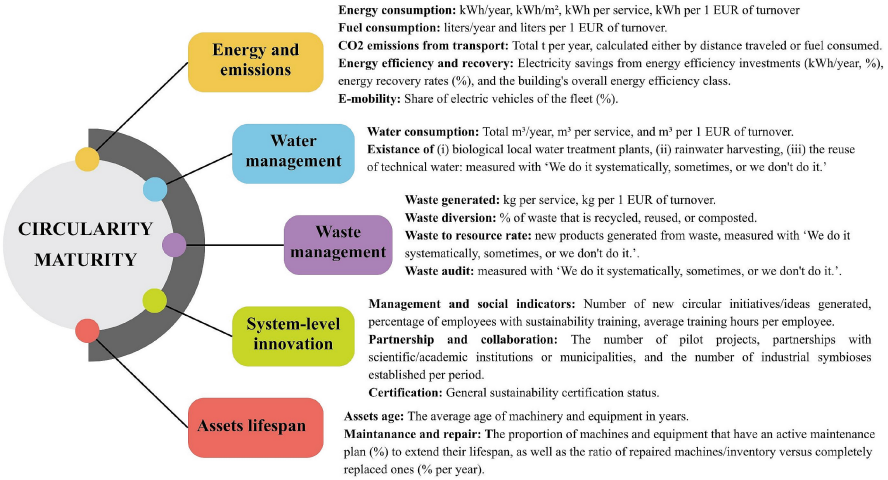


Fig. 1. Circularity Maturity Assessment: Dimensions and indicators. Study limitations: The study investigates three highly specialised, national-level public facilities in Latvia.

3 Results

Based on the Participatory Action Research (PAR) data gathered during the one-year study of the three facilities:

- The Turaida Museum Reserve is a state-accredited museum and a highly protected cultural monument of state significance, operating directly under the Ministry of Culture of Latvia. The facility maintains and restores historical monuments, buildings, and landscapes across 43.63 ha, offering insights into over a thousand years of local history, ethnography, and archaeology. This natural monument or national museum is located in the Gauja National Park area. The museum holds a European heritage label. Institutional web page: https://turaida-muzejs.lv/en/.
- The Riga National Zoological Garden, a 20-ha municipal institution located in Mežaparks, is the only national zoological garden in Latvia. Housing around 3,400 animals across 410 species, RigaZoo's core missions are fauna demonstration, ex situ species conservation, ecological education, and recreation. RigaZoo is an active participant of the European Endangered Species Program (EEP) and the European Association of Zoos and Aquaria (EAZA). Institutional web page: https://rigazoo.lv.
- The Bobsleigh and Luge Track "Sigulda" is located in the Gauja National Park area. It is a specialised winter sports facility. The Latvian Ministry of Education and Science owns the institution through the state enterprise "Latvijas Nacionalais sporta centrs". Built in 1986, this unique Eastern European sports facility features a 1,200 + 220 m artificial ice track. The track has 16 curves across 6,330 m^2. As a highly capital- and energy-intensive infrastructure, it consistently has service costs that exceed turnover. The Track remains heavily dependent on government support and the availability of EU structural funds for capital investments. Institutional web page: (https://www.bobtrase.lv/).

Grouping by management areas allows for evaluation of the system rather than of separate indicators. Overall, studied organisations operate at a "Growth" stage, meaning circular practices are integrated into daily operations but lack a common, unified, and systemic strategic framework. For example, regarding waste management, all three facilities have practical daily practices (such as composting bio-waste on-site, reusing branches for animal feed or as wood chips, and using reusable containers). However, despite these efforts, they lack systematic data, and no one conducts regular waste audits. The results of the case study are summarised in Table 1.

Table 1. Circularity maturity assessment of case studies

Circularity Trait	National Sports Facility	National Zoological Garden	National Museum
Resource Efficiency	Growth	Growth (Energy)/Basic (Water)	Growth
Extending Asset Lifespan	Professional	Professional	Growth (Near Professional)
Waste Prevention	Growth	Growth	Growth
System-Level Innovations	Growth	Growth-Professional	Basic - Growth
Overall Maturity Level	Growth	Growth-Professional	Basic - Growth

Water management at the National Zoological Garden scores the lowest. Upgrading from traditional consumption to a circular system (e.g., rainwater harvesting and greywater reuse for animal enclosures) requires substantial capital-intensive infrastructure modifications. The facility cannot self-fund these changes.

All three institutions incur high infrastructure costs and strongly depend on state or municipal funding. They demonstrate their highest maturity by extending asset lifespans and embracing a strong repair culture. Public funding constraints drive this practice. Since they lack free capital to purchase new equipment or undertake major infrastructure overhauls (such as replacing the refrigeration units at the sports track), maximising the lifespan of current assets is an economic survival mechanism. This approach coincidentally aligns with high-circularity practices.

None of these facilities can independently achieve an overall "Professional" maturity level. They are locked into unprofitable public-service models. Achieving systemic circularity, like renewable energy installations or water recycling systems, strongly depends on external funding (EU or state/municipal). Table 2 presents further analysis of circularity potential, strengths, and barriers in the context of CE practices.

Table 2. Circularity potential: identified strengths and barriers

Circularity Potential	National Sports Facility	National Zoological Garden	National Museum
Strength	Longevity of professional equipment	Infrastructure lifespan extension and "repair and reuse" culture	Asset longevity and a strong "repair and reuse" culture
	Targeted operational efficiency	In-house grown food loops, potential for organic waste loops	Exhibition items from recovered materials
	Data tracking of resources	Strong systemic vision	Educational program integrated
Barriers	Resource-consuming ice maintenance	Historical water management system	Heritage conservation regulations
	High infrastructure intensity	Capital-intensive, infrastructure	Strict climate regulations
	Structural financial deficit	Low-waste diversion practices	Regulated state procurements

4 Conclusions and Discussion

This study reveals the potential for circularity and sector-specific aspects for three resource-intensive public facilities. To improve circularity, zoological gardens must prioritise advanced water management and organic waste loops. Sports facilities require significant infrastructure modernisation. Museums need to focus on digitalisation and cross-sectoral resource sharing. This approach addresses the unique challenges posed by strict heritage conservation regulations.

State public procurement laws and strict cultural or natural conservation mandates heavily restrict institutional operations. These institutions lack the internal capital to fund massive, systemic infrastructure modifications. It is typical for them to try to solve major challenges on their own. Such challenges include high demand, seasonal fluctuations, and inefficiently managed infrastructure. This supports only basic, surface-level circularity rather than true, systematic transformation.

Transitioning resource-intensive public facilities to circularity requires strategic financing [2, 9], such as utilising the Energy Service Company (ESCO) model, in which efficiency upgrades are paid for through energy savings. [15].

Applying such energy optimisation models within sprawling cultural heritage sites like Turaida Museum Reserve requires a more selective approach. Strict mandates for temperature, humidity, and cultural conservation are in place. Comprehensive energy retrofits in delicate historical structures are virtually impossible. Following successful operational examples from European open-air museums such as Skansen [14] and Maihaugen [7], heritage facilities should implement centralised, real-time energy monitoring. Efforts should focus strictly on optimising newer, non-historical administrative buildings while leaving heritage assets untouched.

Zoological gardens face unique barriers driven by strict animal welfare regulations and high energy consumption. This is especially true in tropical houses and aquariums. These factors complicate ESCO investment returns and increase financial risk. Integrating advanced energy-efficiency models in these facilities is hindered by systemic barriers. These include a lack of precise historical consumption data, the complexity of state public procurement laws, and institutional inexperience with long-term contracts. Overcoming these challenges requires blending private financing models with municipal co-financing and national support programs. The success of Finish Korkeasaari Zoo [6] demonstrates a strong commitment to circularity. This institution prioritises carbon-neutral operations, green procurement, organic waste recovery, and closed-loop feeding.

For highly energy-dependent infrastructure like the Sigulda Bobsleigh Track, modernising compressors and recovering heat from its 1,200-m artificial ice track offer massive potential. This is similar to the 20% electricity savings achieved at the Innsbruck track. However, the Sigulda facility is technologically ageing and highly capital-intensive. Deep modernisation cannot rely solely on private ESCO partnerships. It must also have crucial backing from state and EU structural funds, which are already available in Latvia.

For the ESCO model to work effectively in the public sector, stable, measurable energy consumption data is needed. Accurate historical records are also necessary to forecast savings. Clear legal conditions must be in place. In Latvia, barriers may include complex public procurement processes, a lack of experience and distrust of long-term contracts, restrictions on historical buildings, and the absence of precise consumption monitoring. Therefore, in Latvia, the ESCO model for resource-intensive public facilities should be supplemented by EU funding, state support programs, and municipal co-financing.

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Data-Driven Inverse Design of a Material-Efficient CAR1 Friction-Yielding Damper

Magdalini Titirla(✉) and Walid Larbi

Mécanique, Acoustique, Contrôle et calcul Scientifique (MACS), Conservatoire National des Arts et Métiers (CNAM), Paris, France
magdalini.titirla@lecnam.net

Abstract. This study presents a data-driven inverse design approach for the development of a material-efficient CAR1 friction-yielding damper, a passive energy dissipation device used to enhance the seismic performance of structures. The damper is composed of simple and potentially recyclable materials, and its axial control force and energy dissipation capacity depend on the appropriate selection of its design parameters. The CAR1 damper is characterized by thirteen design variables, resulting in many possible configurations. Traditional design approaches rely on predefined parameter combinations, which may lead to non-optimal material use. To address this limitation, a global sensitivity analysis is first performed to identify the most influential parameters affecting the damper's performance. Based on the generated dataset, an Artificial Neural Network (ANN) model is developed to approximate the relationship between design parameters and damper performance. The trained ANN is then used in an inverse design framework to identify parameter combinations that achieve target performance levels while minimizing material usage. The proposed methodology supports data-driven decision-making for the design of efficient seismic dampers, contributing to the development of resilient and resource-efficient structural systems

Keywords: Material-efficient design · Damper CAR1 · Fourier Amplitude Sensi- tivity Test · Data-Driven design · ANN inverse optimization

1 Introduction

Seismic risk encourages the installation of passive energy dissipation devices to mitigate earthquake damage [1–4]. Friction dampers are successful because of their simplicity, durability, and independence from power. They transform kinetic energy into heat, which reduces forces and displacements. Their performance is determined by interactions among geometric, material, and frictional characteristics [5–9]. Optimising these parameters to satisfy seismic performance targets remains a hard task.

The objective of this study is to optimize the mechanical behavior of the CAR1 friction damper [10], a representative passive energy dissipation device, using an integrated approach combining FE modeling, ANN-based surrogate modeling, global sensitivity

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analysis, inverse identification, and optimization. The validated FE model [11] serves as the reference to predict nonlinear damping behavior and generate a simulation dataset for training the ANN model, which reproduces the damper response at a much lower computational cost. Global sensitivity analysis identifies the most influential parameters and filters out negligible ones [12]. The trained ANN is then employed in an inverse design framework to discover parameter combinations that reach desired performance levels (while minimizing material consumption.

2 Damper Configuration

Figure 1 presents the configuration of the device proposed by Papadopoulos et al. [10], highlighting the external tube (Element A), inner shaft (Element B), and multiple groups of superimposed blades (Elements C) that make up the device. An elastoplastic flexural deformation of the stacked blades connecting elements A and B allows for the relative movement between the external tube and the internal shaft. The constitutive law of diagonal bracing under axial stress is determined by the total number, size, and elastoplastic characteristics of the superimposed blades. Thirteen parameters in the CAR1 damper alter its mechanical behavior (Table 1).

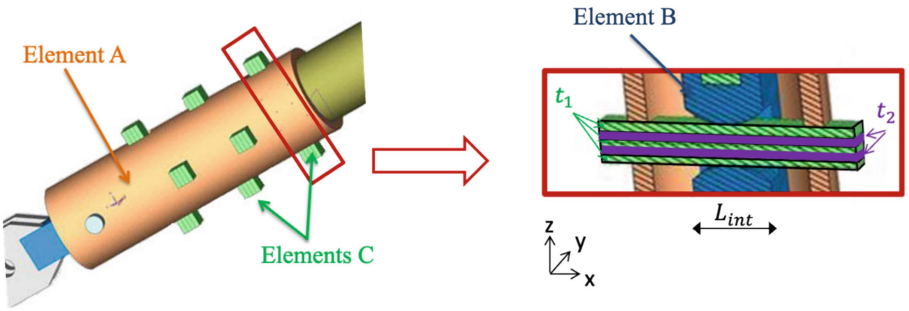


Fig. 1. Damper CAR1.

Table 1. Description of the investigated parameters.

Parameters	Definition	Unit	Min-Max value
t_1	Thickness of a main material blade.	mm	1–20
t_2	Thickness of a secondary component blade.	mm	0–10
N_1	The main material's blade count.	–	2–10
N_2	The secondary material's blade count.	–	0–10
μ	Friction coefficient in the contact area.	–	0.01–0.70
L_{int}	The inner shaft's length.	mm	40–90

(*continued*)

Table 1. (*continued*)

Parameters	Definition	Unit	Min-Max value
E_1	The fundamental material's Young's modulus.	GPa	100–201
E_2	The secondary material's Young's modulus.	GPa	100–201
v_1	Primary material's Poisson's ratio.	–	0.3–0.34
v_2	Poisson's secondary material ratio.	–	0.3–0.34
σ_1	The fundamental material's yield stresses.	MPa	170–215
σ_2	The secondary material's yield stresses.	MPa	170–215
U	Midspan deflection of the blade group.	mm	0–34

3 Artificial Neural Network

The finite element (FE) model was employed in previous studies to analyze the behavior of the device under the individual and combined effects of multiple parameters, demonstrating the importance of numerical simulations in obtaining results that are difficult to achieve experimentally [13, 14]. However, this approach involves a high computational cost. To address this limitation, an artificial neural network (ANN) was developed as a surrogate model to approximate the FE results [15–17]. The ANN was trained to capture the nonlinear relationship between 13 input parameters (Table 1) derived from FEM simulations and a single output variable representing the axial load. A dataset of 3200 simulations was used, with 70% allocated for training and 30% for testing. Several network architectures were evaluated through a parametric study to optimize performance, using standard error metrics such as mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE), correlation coefficient (COR), and coefficient of determination (R2) [18, 19]. Figure 2 represents the chosen architecture (13–10–4–2-1), where the three hidden layers consist of 10, 4 and 2 neurons, respectively [12] (Fig. 3 and Table 2).

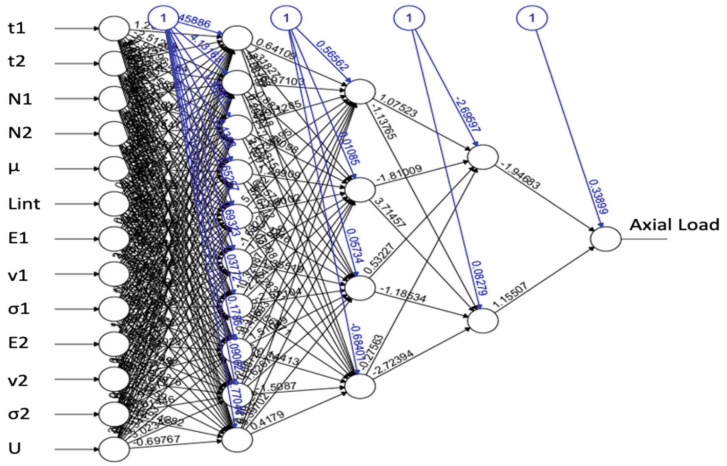


Fig. 2. Artificial Neural Network Model capable of predicting the axial load on the CAR1 damper.

Table 2. Standard error metrics used to evaluate the performance of the ANN.

COR	MSE	RMSE	MAE	R2
0.99416	0.00025	0.016	0.01179	0.98674

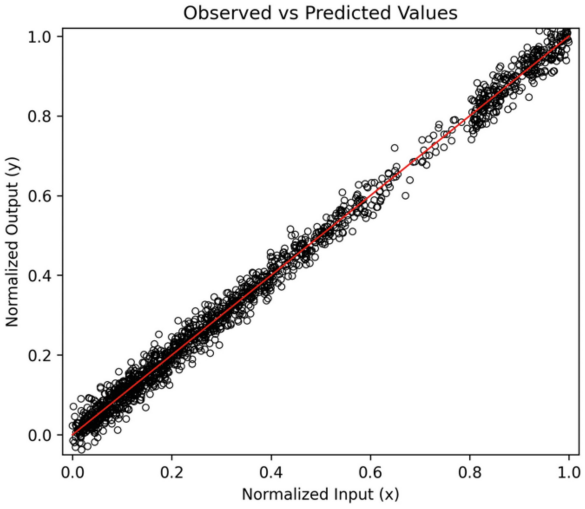


Fig. 3. Graph of Actual vs. Predicted values from ANN.

4 Inverse ANN to Material-Efficient

Based on previous global sensitivity analyses, the device exhibits strongly nonlinear behavior. The parameters exerting the most significant influence on its response are the coefficient of friction, the contact surface area, and the number and thickness of the superimposed blades [12]. The blade material—either a single material or a combination of two different materials—is selected according to the specific structural requirements and characteristics of the building. Notably, this damper has been designed using simple, cost-effective materials such as steel and/or brass. The target displacement and axial load are also dependent on the building's characteristics and are therefore treated as known quantities. Consequently, in the ANN-based inverse problem, eight values are considered known, while the optimization focuses on determining the combination of six parameters ($t_1, t_2, N_1, N_2, \mu, L_{\text{int}}$) that achieves the target axial load (stage 1 of optimization) while minimizing the quantity of material (stage 2 of optimization).

The inverse problem was solved using a genetic algorithm (GA) due to the nonlinear and potentially ill-posed nature of the ANN mapping [20]. While the forward model used 13 input variables, the inverse analysis estimated six unknowns, with the remaining variables fixed from sensitivity analyses. The GA minimized the discrepancy between the ANN output and the target response by performing a global, derivative-free search, making it well suited for complex error landscapes with multiple local minima where gradient-based methods may fail. Figure 4 shows the two-stage optimization methodology with an emphasis on material-efficient. Reducing material volume enhances sustainability in the built environment by lowering raw material use, embodied energy, and waste generation. It also increases resource efficiency and may simplify the reuse, transport, and recycling of the damper at the end of its lifecycle, supporting circular economy objectives.

To validate this study, the authors examined whether the device configuration proposed by Titirla [21] provides an optimal solution in terms of material used. That study investigated an existing building and suggested several damper arrangements to strengthen the first floor in the Y–Y direction. A single CAR1 damper required 325 kN for a target displacement of 23 mm, using five groups of superimposed blades. The proposed configuration used three steel plates (8 mm thick) and two brass plates (3 mm thick) with internal length 30 mm and friction coefficient 0.34. The study does not aim at optimizing the number of groups, but rather at evaluating the performance of the existing configuration (target Axial Load for a target displacement) while minimizing the material used.

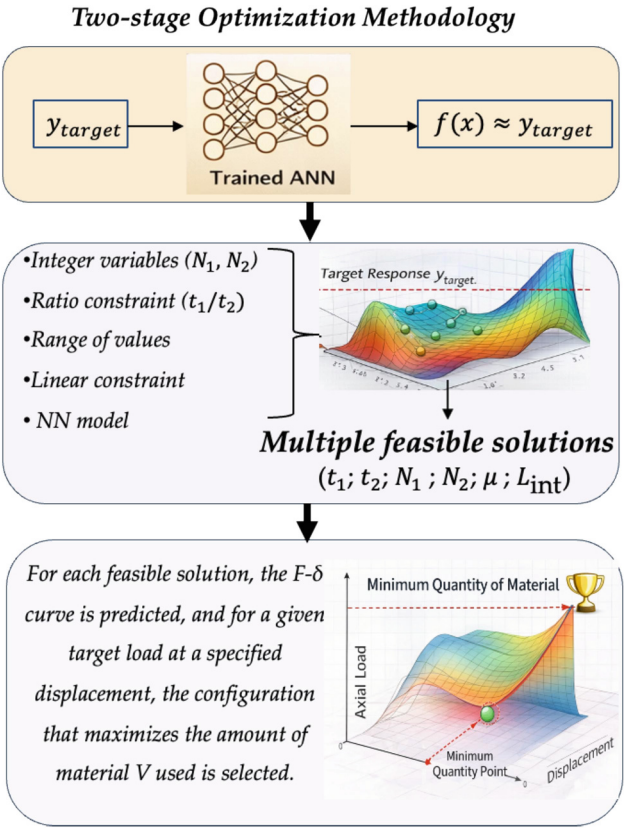


Fig. 4. Two-stage optimization methodology of inverse ANN with an emphasis on material-efficient.

Table 3 presents four possible solutions based on the Stage 1 configuration and the optimal Stage 2 configuration. The indices "1" and "2" denote steel ($E_1 = 201$ GPa, $\nu_1 = 0.3$, $\sigma_1 = 215$ MPa) and brass ($E_2 = 100$ GPa, $\nu_2 = 0.34$, $\sigma_2 = 170$ MPa). Configuration No. 2 is the best solution for the least material volume while achieving the axial load at the specified target displacement.

Table 3. Description of the investigated parameters.

Codename	t1 (mm)	t2 (mm)	N1	N2	μ	Lint (mm)	V (m^3)
No. 1	5.3	1.1	3	2	0.16	50	0.01849
No. 2	8	3	3	2	0.34	27	0.00915
No. 3	7.7	5	4	3	0.1	22	0.0095
No. 4	7.9	2.8	3	2	0.20	48	0.0275

Reducing the material volume is particularly significant from a sustainability perspective, as it directly lowers raw material consumption, and the associated embodied energy and carbon emissions linked to extraction, processing, and manufacturing. In the context of the built environment, a lighter and materially efficient damper contributes to resource efficiency by achieving the required structural performance with fewer inputs, thereby supporting circular construction principles. Moreover, minimizing the quantity of material can facilitate future reuse and disassembly, since smaller and lighter components are generally easier to transport, replace, inspect, and reintegrate into new structural systems. Reduced material complexity and quantity may also improve recyclability at the end of the component's service life (after an earthquake) by decreasing waste generation and simplifying material recovery processes. Consequently, the optimization strategy not only enhances mechanical efficiency, but also aligns the damper design with broader sustainability objectives in contemporary construction, including waste reduction, lifecycle performance improvement, and responsible resource management.

5 Conclusions

The following are the main scientific accomplishments and conclusions:

(i) Based on previous FE datasets [11] that was valided by experimental set-up, an artificial neural network (ANN) was trained as a computationally efficient surrogate, achieving a strong balance of complexity and accuracy. The optimized architecture was 13–10–4-2-1 with three hidden layers of 10, 4, and 2 neurons.
(ii) The device's response is nonlinear, with the main influencing factors being the friction coefficient, contact area, and the number and thickness of superimposed blades.
(iii) Using an ANN-based inverse model, six input parameters were optimized to achieve a target axial load while minimizing the volume of material used in the damper. A two-stage approach was employed: first, a genetic algorithm generated feasible solutions under integer and ratio constraints; second, the resulting configurations were evaluated based on both load–displacement performance and total material volume to identify the optimal design.
(iv) Minimizing material volume supports sustainability in the built environment by reducing raw material consumption, embodied energy, and construction waste. It also improves resource efficiency and can facilitate reuse, transportation, and recyclability of the damper at the end of its service life, aligning the design with circular economy principles.

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On the Decay Potential of Wooden Components Exposed to Outdoor Environment in Greece: Enhancing Existing Estimations and Examining their Temporal Trend

Georgia Nikolitsa and Christina Giarma(✉)

Laboratory of Building Construction and Building Physics, Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
chgiarma@civil.auth.gr

Abstract. The estimation of the degradation potential of building materials and components induced by the climatic conditions in a region, is a major step towards climate adapted, durable and resilient structures. The investigation of this potential's evolution in time supports, in view of the advancing climate change, the design of building elements able to respond to future conditions. Such efforts are very important when wood-based components, the use of which can be highly beneficial regarding circularity and sustainability in the built environment, are concerned. In this study, the decay potential of above ground wooden elements in Greece is examined. Building on the findings of a previous study, which provided such estimates based on daily climatic data over the period 1985–2004 for 33 locations in Greece, this work expands the calculations' basis with the inclusion of daily climatic data for the period 2005–2022. The studied sites are slightly lower in number but still distributed across Greece. The index proposed by Scheffer is used to provide estimations of the decay potential at these sites. An existing dose-response model is additionally applied for some of them. The calculations are performed based on the available data for larger periods between 1985–2022, and for successive smaller intervals within it. Hence, estimations for the examined potential are produced using a broadened climatic database, and its temporal trend over the last decades is identified.

Keywords: Above Ground Wooden Components · Decay Risk · Hygrothermal Conditions · Scheffer Index · Variation of Decay Potential in Time · Greece

1 Introduction

The design and construction of durable, resilient and adaptable to future climatic loads building components lie in the core of circular and sustainable practices in the building sector. The efficient implementation of the relevant strategies depends heavily on the reliable estimation of the actual and foreseen deterioration potential induced by the exposure and working conditions.

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The degradation risk is obviously material-dependent, as different materials are not equally susceptible to every climatic factor. Wood has been the focus of many studies in this regard, e.g. [1–12]. In the context of these studies, various approaches have been adopted, including the calculation of decay potential indices and or the employment of dose-response models for the quantified estimation of the decay potential of wooden components that are exposed to the outdoor climatic loads. On this basis, the risk for the above ground wooden components has been approached for several areas in the world, and maps have been produced for specific countries or broader regions (e.g. [1–7, 9, 10]). In several of the relevant works, the impact of the differentiation of climatic conditions over time has been included to various degrees (e.g. [5–7]).

Recently, relevant results have been produced for several sites in Greece [5] based on daily climatic data for the period 1985–2004 and employing the widely recognized and used Scheffer Index (SI) [1], as well as two dose-response models [8–12].The present work builds upon the existing estimations by extending the climatic database with the addition of more years. The presented SI values are calculated on the basis of daily climatic data ranging from 1985 to 2014 for 25 sites in Greece. For 6 out of those sites, the calculations extend to 2022 using the available climatic data, complemented by the results derived from the implementation of one dose-response model for the entirety of the 38-years period. These results extend the database for the decay potential estimation at the examined sites, including more recent periods, and further support the derivation of conclusions on the timely evolution of the estimated risk.

2 Materials and Methods

2.1 Approaches Adopted for the Estimation of the Decay Potential of Wood

Scheffer Index. A widely used index for the representation of the decay potential of wooden elements above ground is Scheffer Index (SI) [1], based on which relevant maps have been produced for several regions. SI indicates the "*relative potential of a climate to promote decay of off-the-ground wood structures*" [1] and is calculated via Eq. (1) [1]:

$$SI = \frac{\sum_{i=Jan}^{Dec}[(T_i - 2)(D_i - 3)]}{16.7} \quad (1)$$

where Ti [°C] stands for the average monthly temperature for each month of the year (i = January,…,December), and Di [−] represents the average number of days with considerable rainfall (height ≥ 0.25 mm) for each month of the year. Negative values of the product [(Ti-2)(Di-3)] are excluded from the calculation [1]. In this work, SI is the main metric used for the estimation of the decay potential at all the examined sites and for the analysis of the appearing temporal trends.

Dose-Response Model. A dose-based approach [11–12] combined with a simplified dose-response model for the estimation of the decay potential at any site [8–9], have been employed, as a complementary metric to Scheffer index, for a small number of sites. In the core of this model lies the expression of the impact of the moisture content and temperature of wood to its decay process as daily doses (adoption of a dose-response

approach, based on experimental measurements [11]). The temperature and the moisture content of timber are derived on the basis of the main relevant factors characterizing the local climate. This way, the daily dose approach indicates the local climate-induced influence on the potential wood decay process. The calculations are based on daily data, and for each day of the examination period the daily dose is derived from Eqs. (2), (3), (4) [8–9]:

$$D(t_i) = D(T(t_i)) \times D(u(t_i)) \tag{2}$$

$$D(T(t_i)) = \begin{cases} 0, \, if \; T(t_i) < 0°C \\ T(t_i)/30, \, if \; 0°C \leq T(t_i) \leq 30°C \\ 1, \, if \; 30°C < T(t_i) \end{cases} \tag{3}$$

$$D(u(t_i)) = \begin{cases} (u(t_i)/30)^2, \;\; if \; u(t_i) \leq 30\% \\ 1, \, if \; u(t_i) > 30\% \end{cases} \tag{4}$$

In this set of equations, $T(t_i)$ [°C] and $u(t_i)$ [%] represent the daily temperature and moisture content of the studied element, respectively. $T(t_i)$ is assumed to be equal to the daily global air temperature (i-th day) [9], while the daily moisture content of the wooden element is calculated according to the process used in, among others, [9, 10] and shown in Fig. 1. $D(t_i)$ represents the total daily dose calculated for the i-th day of the examined period, with $D(T(t_i))$ and $D(u(t_i))$ standing for the temperature and the moisture-content contribution to the daily burdening for day i, respectively. For any period of analysis, the total dose equals the sum of the daily doses calculated for this period. It is interesting to note that, in this model, also the air relative humidity (i.e. not only data relevant to rainfall) at a site contributes to the final estimations (Fig. 1).

2.2 Climatic Data and Examined Sites

The calculations of SI and of the total daily dose with the use of the equations that are presented in Sect. 2.1 are based on climatic data of daily time resolution, provided by H.N.M.S. (Hellenic National Meteorological Service). Specifically, the average daily air relative humidity and temperature, as well as the daily rainfall for each day of the examined time period are used in the calculations.

The examined period extends from 1985 to 2022, covering more than 3 decades. The respective calculations, along with additional ones, have been performed for the years 1985–2004 in a previous study [5]. The expansion of the calculation basis in the present work serves to both consider a broadened and more recent time period, as well as to investigate the patterns, if any, of the decay potential's variation with time.

In this study, the decay potential for wood exposed to outdoor conditions is examined at 25 sites, spatially distributed over Greece (Table 1). The selection of these sites, less in number than those included in [5], is based on an effort to examine the conditions prevailing in areas of various topographical and climatic characteristics, and on the availability of the required climatic data mainly for the period 2005–2014.

Specifically, in the provided records of daily climatic data for each site, there were days with missing information. The days with at least one of the three variables (temperature, relative humidity, rainfall) missing were excluded from the calculations. The

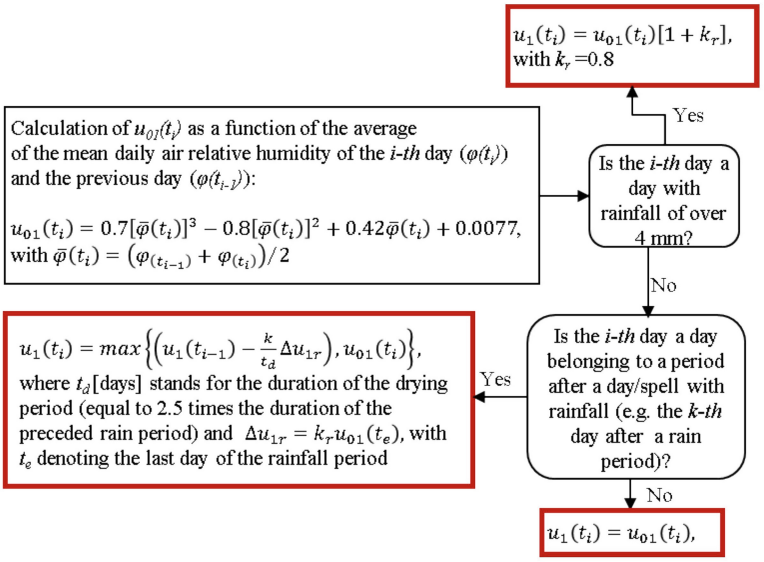


Fig. 1. Process for the calculation of wood's moisture content. All the elements included in the figure (equations, assumptions, etc.) are those ones used in [9, 10]. The figure is based on a relevant one appearing in [5].

Table 1. The investigated stations/sites, spatially distributed across Greece.

Site/Station	Latitude	Longitude	Site/Station	Latitude	Longitude
Agrinio	38.61	21.38	Kerkyra	39.61	19.91
Alexandroupolis	40.86	25.95	Larisa	39.65	22.46
Araxos	38.08	21.25	Mytilini	39.05	26.60
Argostoli	38.13	20.50	Naxos	37.10	25.37
Arta	39.16	21.00	Rodos	36.40	28.09
Athens (Hellinikon)	37.89	23.74	Samos	37.69	26.92
Chania (Souda)	35.53	24.15	Serres	41.08	23.53
Chios	38.35	26.14	Skyros	38.96	24.49
Drama	41.15	24.15	Tanagra	38.34	23.56
Heraklion	35.34	25.18	Thessaloniki (Mikra)	40.53	22.97
Ioannina	39.69	20.83	Tripoli	37.52	22.40
Kalamata	37.07	22.02	Volos (Aghialos)	39.22	22.79
Kavala (Chryssoupoli)	40.92	24.62			

calculation of SI is based on averaging daily data over years per month; in order to ensure the representativeness of results and the comparability of the index' values that

are calculated for the examined sites, months and years having several days with missing data were not taken into consideration as a whole. This approach led to the exclusion of 8 sites examined in [5] from the current study, as the information on the climatic conditions at them for 2005–2014 was not complete or adequate in this context. For the 25 examined sites, SI is calculated based on data for the years 1985–2014. Out of these 25 sites, 6 were selected to be examined with the use of climatic data extending also to 2015–2022. These are the 6 sites for which the dosimetric model was also applied. Their selection was mainly based on data availability and completeness for both the periods 2014–2022 and 1985–2022, and on their distribution across the country (so that they can serve as a basis for future research efforts).

3 Results and Discussion

3.1 Scheffer Index Values for the Examined Sites

In Table 2, the calculated values of SI at the examined sites based on daily data for the periods i) 1985–2004 [5] and ii) 1985–2014, are presented.

Table 2. Scheffer Index values calculated for the examined sites based on the available daily data for the years 1985–2004 (as published in [5]), and for the years 1985–2014.

Site/Station	1985–2004	1985–2014	Site/Station	1985–2004	1985–2014
Agrinio	30.74	31.38	Kerkyra	37.83	44.59
Alexandroupolis	12.79	16.52	Larisa	23.07	24.91
Araxos	31.06	33.60	Mytilini	18.87	19.90
Argostoli	39.58	41.77	Naxos	18.33	20.12
Arta	36.51	37.46	Rodos	24.96	25.00
Athens (Hellinikon)	14.37	14.63	Samos	20.62	22.72
Chania (Souda)	29.58	29.87	Serres	28.71	32.22
Chios	13.83	14.56	Skyros	13.39	15.14
Drama	33.20	38.87	Tanagra	18.78	20.40
Heraklion	27.44	30.57	Thessaloniki (Mikra)	23.04	30.28
Ioannina	37.52	38.09	Tripoli	22.79	24.70
Kalamata	32.86	33.22	Volos (Aghialos)	21.50	23.80
Kavala (Chr/poli)	17.80	21.47			

Table 2 shows a consistent increasing trend for the decay potential across all examined sites when the climatic data for the years 2005–2014 are included in the calculations. While the recorded increase is borderline in some cases (e.g. Rodos), it reaches very

high percentages for some sites. For example, Thessaloniki's SI value that is derived considering the years 1985–2014 is by more than 30% higher than the one based on the period 1985–2004. An interesting observation is that the inclusion of the decade 2005–2014 in the calculations leads to a percentage increase of more than 20% for three sites, all belonging to the northern part of the country. Furthermore, the values of SI that had been derived for these three sites based on the data for the years 1985–2004 belong to the lower half of the respective ones that had been calculated for the list of the examined sites considering the same time period [5].

Notably, this increasing trend must be evaluated also in absolute numbers. As reported in [1], based on the index' value, the severity of the exposure conditions can be ranked in 3 classes: for values lower than 35 the decay potential is considered low; SI higher than 65 corresponds to high decay potential; all other cases indicate intermediate potential. At one site (Drama), the class of the decay potential changes from low to intermediate when the data for the decade 2005–2014 is included in the calculations. In some other cases, although the severity of exposure remains in the same category as before, the increase in the index' value is significant, reaching 6–7 units.

These results outline an increase in the decay potential for wood across the country when more recent data are included in the calculations. In order to further investigate whether this trend is consistent and continuing in time, a second series of calculations was performed taking into consideration also the period 2015–2022. This set of calculations was performed for 6 sites. Evidently, the calculation basis for these sites is even more expanded and the derived results outline the decay potential also for very recent periods. It must be highlighted that this analysis is not exhaustive in terms of the examined sites, but it serves as an indications' basis. The SI values calculated for different intervals in the period 1985–2022, and for its entirety, are listed in Table 3.

Table 3. SI values at 6 sites, based on the available climatic data for 1985–1994 [5], 1995–2004 [5], 2005–2014 and 2015–2022; the results for the period 1985–2022 are also presented.

Site/Station	1985–1994	1995–2004	2005–2014	2015–2022	1985–2022
Alexandroupolis	13.56	13.30	24.82	38.79	20.71
Heraklion	24.44	30.84	37.05	22.98	28.96
Ioannina	34.66	40.16	41.21	97.33	48.23
Kavala (Chryssoupoli)	17.78	19.27	29.17	33.79	23.21
Larisa	23.05	24.21	29.18	48.21	29.62
Mytilini	16.01	21.84	23.10	22.65	20.47

The results shown in Table 3 should be interpreted in combination with the ones listed for these 6 sites in Table 2. For all 6 sites, the SI values based on the expanded climatic base are higher than the respective ones derived for the years 1985–2004. This indicates a shift towards increasing values as time passes. In fact, the expanded database provides a more representative image for each site, enhancing the observation of the increasing decay potential. It is interesting to investigate whether this increase is due to

the increase in the number of days with rainfall, temperature or both. An initial calculation for Ioannina shows that both parameters are increased in 1985–2022 compared to 1985–2004, but this finding is location specific; the relevant investigation must be expanded to more sites for a safer general conclusion to be derived.

At least for the 6 sites listed in Table 3, the increase is not linear or uniform in the individual intervals constituting the larger periods. At one site (Heraklion), the value based on years 2015–2022 is lower than the one for 2005–2014. This trend is marginally the same for Mytilini, while it is strongly reversed for the other stations. Notably, these calculations can be treated only as indications since, among others, the period 2015–2022 is not even 10-years long, i.e. very short for the respective results to be considered as more than indications. Also, this analysis should be accompanied with results for more stations in Greece.

3.2 Application of the Dosimetric Model and Derived Results

In order to account for the different number of days considered for each site, for each station the mean daily dose is calculated. It is derived by dividing the total dose at each site by the number of days that were considered within its calculation. Since the analysis in this work does not aim at the doses themselves as an element of the actual decay estimation, the presented results focus on the study of the mean daily dose variations when the more recent data are also included in the calculations. The mean daily doses that are calculated based on the data for 1985–2004 [5] are compared with those derived for 1985–2022 for each site. Their percent variations are shown in Table 4.

Table 4. Percent variation of the mean daily doses at the 6 examined sites considering the period 1985–2004, when the data for the years 2005–2022 are also included in the calculations.

Site/Station	Alexandroupolis	Heraklion	Ioannina	Kavala (Chr/poli)	Larisa	Mytilini
[%] variation of mean daily dose	16.8%	20.0%	24.0%	15.0%	14.9%	−1.1%

The values shown in Table 4 enhance the image of a general trend of increase introduced by the SI values. The borderline decrease for Mytilini may not be considered to represent a major “breach” to the trend, due to its very low value. The findings for SI suggest similar trends for the majority of the 6 sites; for Mytilini, the respective variation is positive (contrary to the result of the dosimetric approach), but the increase is very low. Notably, even when relative humidity is included in wood’s moisture content estimations, the indicated increase pertains. The differentiations from SI results should be further investigated, considering the impact of relative humidity and the actual model for the calculation of wood’s moisture content on the derived values.

4 Conclusions and Future Research

In this study, the decay potential for wood above ground in Greece has been investigated based on daily data provided by H.N.M.S. for recent decades, with the use of primarily the SI and, secondarily, a dosimetric approach. The analysis focused, apart from analysing the SI results as autonomous values, on the temporal trend of the decay potential. It appears that this trend is generally increasing, suggesting that the change of the climate may indeed induce more severe strains on wooden elements even in areas of generally moderate exposure levels. Generally increasing SI values across Greece had already been indicated in [5], while this tendency of increase in SI values over the years has been identified for other countries as well (e.g [6]).

For this indication to be enhanced, several research steps must be made, including the study of the impact of various calculation parametres on the results (e.g., the mathematical models themselves, the assumptions for the values of the involved quantities). Specifically for Greece, the prevailing conditions at more sites should be investigated with the use of as recent and extended climatic databases as possible, while relevant experimental measurements under the actual prevailing conditions (as performed for various areas of the world) could lead to more reliable estimations.

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Effect of Recycled Materials on the Acoustic Performance of Porous Low-Noise Asphalt Mixtures

Jon Zubizarreta-Azcuna[1(✉)], Ruben Machín-Ledesma[1], Jose Luis Vilas-Vilela[2], Helena Miera-Dominguez[3], Irune Indacoechea-Vega[3], and Daniel Castro-Fresno[3]

[1] ETRA I+D+i (Research and Innovation Unit), Donostia/San Sebastian, Basque, Spain
jon.zubizarreta@etra.eus
[2] University of the Basque Country (UPV/EHU), Leioa, Basque, Spain
[3] GITECO Research Group (Universidad de Cantabria), Santander, Cantabria, Spain

Abstract. Traffic noise is one of the most persistent environmental stressors in urban and interurban corridors, making low-noise and resource-efficient pavements essential for sustainable mobility. This study investigates how the incorporation of several recycled materials—textile fibres, steel slag aggregates, recycled asphalt pavement (RAP) and residual plastics—modifies the acoustic behaviour of two porous mixtures designed for 80 km/h (interurban) and 50 km/h (urban) traffic. The work provides a mechanistic assessment by linking each residue to the functional parameters governing tyre–pavement noise, namely texture spectrum, air flow resistivity and acoustic absorption, integrated through the SPERoN prediction model. In the interurban double-layer mixture, replacing aramid fibres with 0.1% textile fibres preserved mechanical performance, while steel slag—when properly tamised—enhanced absorption ($\alpha \approx 0.60$) and reduced flow resistivity (≈ 400 Pa·s/m), achieving a noise reduction of -6.2 dB, comparable to the virgin mixture (-6.8 dB). In the urban mixture, slag increased texture but improved overall reduction (-2.0 dB), whereas partial binder replacement by plastics raised texture excessively, limiting performance (-0.9 dB). RAP-based mixtures showed balanced behaviour (-1.5 dB). Results demonstrate that residue-induced changes in macrotexture dominate the acoustic response, while increased porosity and absorption can only partially compensate. The study delivers practical design insights for developing sustainable, circular and acoustically optimised asphalt mixtures

Keywords: low-noise asphalt · recycled materials · steel slag · tyre–pavement noise · acoustic absorption · sustainable pavements

1 Introduction

Road-traffic noise is linked to sleep disturbance, stress and heart disease, with more than 12,000 premature deaths annually and more than 113 million people exposed to $>=$ 55 dB(A) due to road traffic in Europe [1].

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Road-vehicle noise has two main contributors—engine noise and rolling noise—and rolling noise becomes dominant above an already moderate speed [1]. For speeds of 30 km/h and above, the road surface is regarded as the most important influencing factor [3].

The pavement's macrotexture strongly influences tyre–road noise, and texture wavelengths map into the sound spectrum even though the overall response is non-linear [1]. A noise reducing asphalt design must also consider porosity, airflow-related resistance (flow resistance or permeability indicators) and acoustic absorption, where higher absorption generally lowers rolling noise when tuned to the tyre emission spectrum and operating speed [1, 2]. A model that combines those factors to predict the noise reduction of a mixture is the hybrid SPERoN model, which combines a physical sub-model with a statistical sub-model [4, 5].

Porous asphalt provides source control by using high air-void content to absorb sound through air-pore-wall interaction, wave-pore interaction and pore-wall resonance [2]. Reported reductions reach up to 5 dB(A) versus dense asphalt and up to 8.5 dB(A) at construction in CPX comparisons, while optimized urban mixtures can achieve around 3 dB compared with conventional roads [1, 2].

However, porous asphalt can lose acoustic efficiency as voids deform or clog with fine particles and debris [2]. Low-noise mixtures must therefore balance noise reduction with rolling resistance and mechanical durability [6]. At the same time, studying the environmental feasibility of new solutions has become a common practice in the construction sector [7] what leads to the need of circular-economy based low-noise asphalt mixture design and validation practices.

This paper evaluates low-noise asphalt mixtures incorporating recycled materials by relating tyre–pavement noise to surface texture, flow resistance (airflow resistivity) and acoustic absorption, with the aim of identifying the influence of different waste materials on noise reduction and providing a knowledge base for the design of sustainable noise-reducing asphalt mixtures.

2 Materials and Methods

2.1 Reference Asphalt Mixtures

Two reference low-noise asphalt mixtures were designed to represent interurban (80 km/h) and urban (50 km/h) traffic while balancing acoustic performance, durability and construction feasibility.

The interurban surface was a double-layer porous asphalt with PA4 as the upper layer and PA8 as the lower layer. Each layer was approximately 20 mm thick (40 mm total), with about 22–23% voids, combining high interconnected porosity with controlled texture to promote absorption and air flow.

The urban surface was a 20 mm dense low-noise mixture with 4 mm maximum aggregate size and about 9–12% voids, selected to reduce texture while maintaining mechanical resistance under braking and acceleration.

Both mixtures used PMB 45/80–65 bitumen and conventional aggregates; they were the baseline for assessing the acoustic influence of the recycled materials.

2.2 Recycled Materials Evaluated

Five recycled-material configurations were assessed as substitutes for conventional mixture components (Table 1). **Recycled textile fibres** from post-consumer waste replaced aramid fibres used to stabilise binder in porous asphalt and prevent drainage.

Steel slag, evaluated as received and after sieving, replaced natural aggregates; sieving was used to better adjust gradation and mixture porosity.

Residual plastics from post-consumer streams partially replaced bitumen in the urban mixture, and **recycled asphalt pavement (RAP)** replaced part of the aggregate fraction while contributing aged binder.

The tested configurations and residue functions are summarised in Table 1.

Table 1. Mixtures and recycled materials evaluated.

Mixture	Traffic environment	Residue incorporated	Function of residue
PA4 + PA8 porous mixture	Interurban (80 km/h)	Textile fibres	Replacement of aramid fibres
PA4 + PA8 porous mixture	Interurban (80 km/h)	Steel slag	Replacement of natural aggregates
Urban low-noise mixture	Urban (50 km/h)	Steel slag	Replacement of natural aggregates
Urban low-noise mixture	Urban (50 km/h)	Residual plastics	Partial binder replacement
Urban low-noise mixture	Urban (50 km/h)	RAP	Replacement of aggregates and aged binder

2.3 Specimen Preparation

The mixtures were produced at laboratory scale following a conventional hot-mix asphalt procedure. Aggregates were batched according to each target gradation and mixed with PMB 45/80-65; hydrated lime and fibres were added to the porous interurban mixtures to improve cohesion and prevent binder drainage. The reference mixtures were composed of coarse and fine aggregate fractions, mineral filler, polymer-modified bitumen and fibres when required. In the recycled mixtures, the corresponding secondary material replaced the conventional component: textile fibres for aramid fibres, steel slag for natural aggregate, plastics for part of the binder and RAP for aggregate/aged binder.

Functional acoustic tests were performed on cylindrical specimens reproducing the layer configuration relevant for surface-related acoustic behaviour. The interurban specimens reproduced the in-service double-layer system, with a PA8 lower layer and a PA4 upper layer of 20 mm each, resulting in a total thickness of 40 mm. The PA8 layer was placed first and the PA4 layer was subsequently added in the same mould, so that the acoustic tests were performed on the final two-layer configuration rather than on isolated layers. The urban mixtures were prepared as single-layer specimens with a

nominal thickness of 20 mm for acoustic and surface-related testing. In all cases, the mixture mass was adjusted to obtain the target thickness and void content of each formulation. Mechanical characterisation, when required, was carried out on specimens prepared according to the corresponding EN 12697 test methods, in order to assess the mixture formulation under standardised laboratory conditions.

Specimens used for ISO 10534-2 had a nominal diameter of 100 mm to fit the impedance tube and maintain plane-wave conditions within the frequency range of pavement-acoustic interest, below approximately 1.8 kHz. The exposed test surface was the tyre-contact surface: the PA4 upper layer for interurban specimens and the compacted wearing surface for urban specimens.

2.4 Acoustic Characterization of Mixtures

The acoustic behaviour of the mixtures was evaluated through the functional parameters governing tyre–pavement noise generation. Three key properties were measured: surface texture spectrum, air flow resistivity and acoustic absorption.

The **surface texture spectrum** was measured on the exposed surface of the specimens using a high-resolution laser scanning device. The resulting surface profiles were processed according to ISO 13473-4 to determine texture levels over the wavelength range relevant for texture-induced rolling noise. For the interurban double-layer specimens, the measured surface corresponded to the PA4 upper layer, whereas for the urban mixtures the surface corresponded to the single compacted layer.

The **air flow resistivity** was determined following DIN EN 29053 by relating the pressure difference generated by air passing through the surface to the flow velocity. The parameter reflects pore connectivity and the ability of the mixture to reduce air-pumping noise.

The **acoustic absorption coefficient** was measured according to ISO 10534-2 using a 100 mm impedance tube. The specimen was placed at the tube end, a loudspeaker generated a plane wave, and two microphones separated the incident and reflected waves to calculate the normal-incidence absorption coefficient as a function of frequency. The coefficient represents the ratio between the sound energy absorbed by the specimen and the incident sound energy. For double-layer specimens, the wave was applied from the PA4 surface to reproduce the in-service orientation.

The maximum absorption coefficient and its peak frequency were recorded. Particular attention was given to the peak frequency, since high absorption is acoustically effective only when it is aligned with the dominant rolling-noise frequency range. Therefore, mixtures with similar absorption coefficients may lead to different predicted noise reductions if the peak occurs outside the most relevant frequency band.

2.5 Noise Prediction Model

The acoustic performance of the mixtures was estimated using the **SPERoN model** [4, 5], which predicts tyre-pavement noise from surface texture, air flow resistivity and acoustic absorption. The measured texture spectra, flow resistivity values and absorption parameters described above were used as input data to estimate the expected noise reduction relative to a reference pavement surface.

In this study, the predicted noise reduction was calculated relative to conventional reference surfaces: SMA11 for interurban mixtures and AC16 for urban mixtures. By combining the measured functional parameters with the SPERoN model, it is possible to evaluate how the incorporation of recycled materials modifies the acoustic performance of the asphalt mixtures.

3 Results and Discussion

The main acoustic results obtained for the studied mixtures are summarised in Table 2.

Table 2. Acoustic performance and predicted noise reduction of the analysed mixtures.

	Speed (km/h)	Air flow resistivity (Pa·s/m)	Acoustic absorption coefficient (−)	Peak absorption frequency (Hz)	Predicted noise reduction (dB(A))
Interurban reference	80	820	0.40	–	−6.8
Interurban with sieved slag	80	398	0.60	656	−6.2
Interurban with unsieved slag	80	1139	0.32	498	−4.8
Urban reference	50	29166	0.10	–	−1.6
Urban with slag	50	11592	0.61	1517	−2.0
Urban with slag and plastics	50	3705	0.73	1743	−0.9
Urban with RAP	50	5256	0.65	1517	−1.5

The reference interurban porous mixture achieved the best overall acoustic performance (−6.8 dB(A)), confirming the effectiveness of double-layer porous asphalt surfaces where interconnected porosity and limited macrotexture contribute to sound absorption and reduced air pumping.

The replacement of virgin aramid fibres with recycled textile fibres did not produce significant changes in the acoustic response of the interurban mixture, while mechanical performance remained acceptable. This result indicates that recycled fibres can successfully perform the stabilising role of conventional fibres without compromising the functional behaviour of the porous surface.

The incorporation of steel slag aggregates had a more pronounced effect on the interurban mixtures. The mixture produced with sieved slag showed the most favourable combination of acoustic parameters, with a relatively low air flow resistivity (398 Pa·s/m) and a high absorption coefficient (0.60), resulting in a predicted noise reduction of −6.2 dB(A).

In contrast, the use of unsieved slag increased air flow resistivity to 1139 Pa·s/m and reduced the absorption coefficient to 0.32, lowering the predicted noise reduction to −

4.8 dB(A). These results indicate that the acoustic benefit of steel slag depends strongly on gradation control and the resulting pore structure.

The surface texture spectra obtained for the interurban mixtures are shown in Fig. 1.

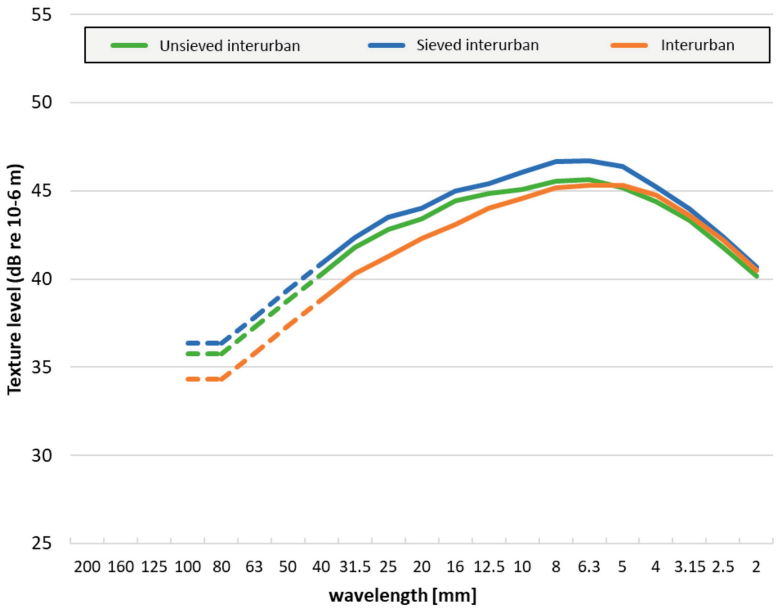


Fig. 1. Texture spectrum of the analysed interurban mixtures.

As illustrated in Fig. 1, the mixtures incorporating steel slag exhibit slightly higher macrotexture levels than the reference porous mixture, particularly in the wavelength range between approximately 10 and 50 mm. The mixture produced with sieved slag presents a more controlled texture spectrum, whereas the mixture with unsieved slag reflects the wider aggregate size distribution and a less homogeneous surface structure. These differences are consistent with the variations observed in air flow resistivity and acoustic absorption.

This comparison shows that the influence of slag cannot be interpreted from texture alone. The sieved slag mixture retained a texture spectrum close to the reference while maintaining a more favourable pore network, whereas the unsieved slag mixture combined higher resistivity with lower absorption. The acoustic penalty is therefore linked to the simultaneous modification of surface texture and internal connectivity.

In the **urban mixtures**, the overall acoustic performance was lower than in the porous mixtures due to the reduced void content and the more closed internal structure. The reference urban mixture achieved a predicted noise reduction of approximately **−1.6 dB(A)** relative to the AC16 reference surface. The higher peak absorption frequencies observed in the urban mixtures are consistent with their lower thickness and different pore structure, which shifts the absorption response towards higher frequencies.

The mixture incorporating **steel slag aggregates** slightly improved the predicted noise reduction to **−2.0 dB(A)**. This improvement suggests that the modified internal structure of the mixture still provides a favourable balance between macrotexture and sound dissipation mechanisms.

However, the incorporation of **residual plastics as a partial binder replacement** produced a different effect. Although the mixture showed increased acoustic absorption (**0.73**) and reduced air flow resistivity (**3705 Pa·s/m**), the predicted noise reduction decreased to approximately **−0.9 dB(A)**. This result indicates that the increase in surface macrotexture associated with the reduced workability of the plastic-modified mixture dominates the acoustic response, offsetting the benefits of the improved absorption.

The mixture incorporating recycled asphalt pavement (RAP) exhibited an intermediate behaviour (−1.5 dB(A)), remaining close to the reference urban mixture and indicating that RAP can be incorporated without a strong acoustic penalty.

Overall, the results demonstrate that the acoustic behaviour of asphalt mixtures incorporating recycled materials depends primarily on how these materials modify the **surface texture spectrum and pore connectivity** of the mixture. Increased acoustic absorption and reduced air flow resistivity can contribute to improved noise mitigation, but only when they are not accompanied by excessive macrotexture. In this sense, the results indicate that **macrotexture is the dominant parameter controlling the final noise response**, while acoustic absorption and air flow resistivity act as secondary compensating mechanisms.

These findings highlight the importance of considering functional acoustic parameters when introducing recycled materials into low-noise asphalt mixtures. Proper control of aggregate gradation, pore connectivity and surface texture is therefore essential to ensure that circular pavement solutions maintain or improve their acoustic effectiveness, providing practical guidance for the design of sustainable low-noise pavements incorporating recycled materials.

4 Conclusions

The results demonstrate that several recycled materials can be incorporated into low-noise asphalt mixtures without necessarily compromising acoustic performance. The acoustic behaviour of the analysed mixtures was interpreted through the functional parameters governing tyre-pavement noise generation: surface texture, air flow resistivity and acoustic absorption.

The replacement of virgin aramid fibres with **recycled textile fibres** proved to be technically viable, maintaining both the mechanical stability and the acoustic response of the porous mixture. This result highlights the potential of recycled fibres as a circular alternative for binder stabilisation in porous asphalt mixtures.

The incorporation of **steel slag aggregates** showed promising results, particularly when the material was properly sieved. The sieved slag mixture presented favourable air flow resistivity and acoustic absorption values, resulting in a predicted noise reduction comparable to that of the reference porous mixture. In contrast, the use of unsieved slag led to poorer acoustic performance due to a less controlled pore structure.

For **urban mixtures**, the influence of recycled materials was more limited due to the lower porosity of the mixture. Steel slag slightly improved the predicted noise reduction,

while mixtures incorporating **residual plastics** showed a decrease in acoustic performance despite increased absorption. This behaviour indicates that excessive macrotexture may dominate tyre–pavement noise generation, offsetting potential benefits associated with improved acoustic absorption.

The **RAP** mixture exhibited intermediate behaviour, indicating that reclaimed materials can be used without significantly affecting pavement acoustic response.

Overall, successful integration of recycled materials in low-noise pavements depends mainly on how they modify **surface texture and pore connectivity**. Proper control of aggregate gradation and mixture design is therefore essential to ensure that circular asphalt solutions maintain or enhance acoustic effectiveness.

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A Novel Sustainability Assessment Framework Tailored to University Campus Environments

Bahareh Hokmabadi[1](✉), Francesca Abastante[1], Dana Al Mamlouk[1], Patrizia Lombardi[1], Beatrice Mecca[1], Valerio R. M. Lo Verso[1], Andrea Moro[2], Maurizia Pignatelli[1], Virginia Pellerey[1], Daniela Santana Tovar[1], and Sara Torabi Moghadam[1]

[1] Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10125 Torino, TO, Italy
s310701@studenti.polito.it
[2] iiSBE Italia R&D, Via Paolo Borsellino 38, 16, 10138 Torino, TO, Italy

Abstract. This paper is based on the preliminary phase of a larger project to develop a version of the ITACA Protocol specifically for university campuses in Italy. This phase is divided into two stages: theoretical and implementation. In the Theoretical part, 44 thematically relevant papers were reviewed in full text, and the indicators used in them were extracted, resulting in 258 unique indicators. The indicators were classified according to the SNTool's categories. Then, their units and frequency of occurrence, defined as the number of papers in which each indicator appeared, were recorded. In the Implementation part, 20 of the most frequently used indicators- for which there was enough data from the Politecnico di Torino (POLITO) - were selected, and the sustainability score of POLITO was calculated based on them. In the next step, a Q-sort analysis was conducted to prioritize 10 SWOT-based actions, and 3 future scenarios were identified. Finally, for all the scenarios, feasibility studies were conducted to assess the improvement and corresponding sustainability scores. The scenario with the highest score was identified as the best option

Keywords: SNTool · ITACA Protocol · SBTool · iiSBE · Sustainability Assessment Framework · Campus Indicators

1 Introduction

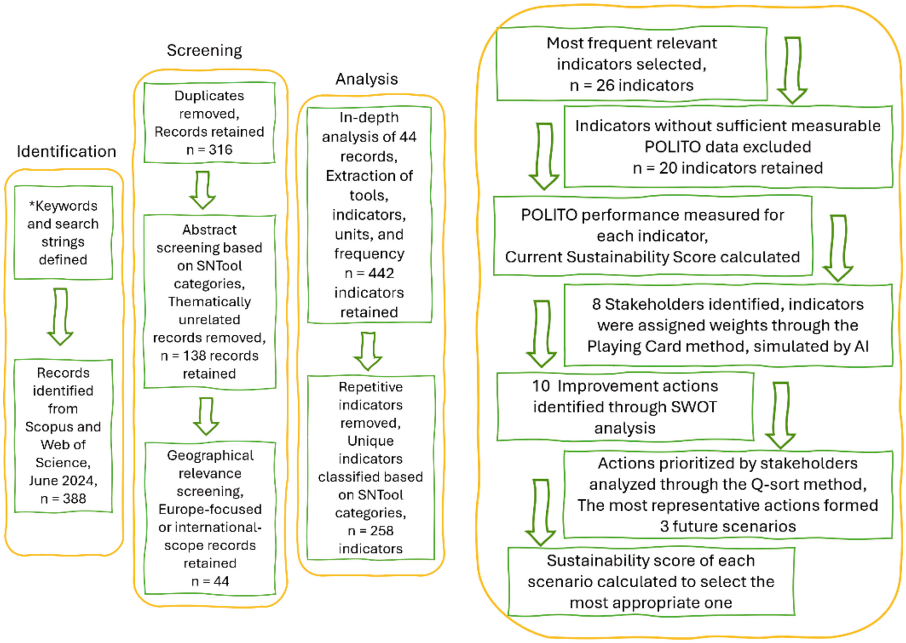
1.1 Aligning the National Sustainability Protocol with University Campuses

A university campus is viewed as a "small city", with flows of people and resources, and a wide range of services—making it an ideal living laboratory where sustainability solutions can be tested before being scaled up to urban and national levels. The ITACA Protocol [1] serves as Italy's green building rating system. ITACA is based on the international model, SBTool [2], which is primarily designed for the assessment of individual buildings. To align this national framework with the scale of a campus, instead of SBTool, its neighborhood/urban counterpart, SNTool [3], was applied. Both tools share the same underlying iiSBE [2] methodology, based on local customization. This work is built upon research conducted in the author's master's thesis [4].

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2 Methodology

Figure 1 a and b show the methodology in the theoretical and implementation phase, respectively.



a. Theoretical phase diagram **b.** Implementation phase diagram

Fig. 1 a. Theoretical phase diagram. b. Implementation phase diagram. *Search strings combined terms related to sustainability assessment tools, university/campus contexts, and sustainability indicators/performance using Boolean operators.

2.1 Implementation Phase

Forming the Indicator Set and Calculating the Categories' Score. The implementation phase began with selecting the most frequently used indicators identified in the literature. Frequency was defined without any fixed numerical threshold, but simply as the number of articles in which each indicator appeared. From this phase, 26 indicators were initially selected. Among them, 20 were retained because sufficient measurable data were available for Politecnico di Torino (POLITO). For each indicator, the performance value was calculated, using formulas or assessment procedures derived from literature, and normalized according to the SNTool scale from −1 to 5. In this scale, −1 indicates performance below the minimum benchmark, 0 corresponds to the minimum benchmark, and 5 represents the maximum benchmark. The benchmark values were not locally calibrated for the Italian context; they were extracted from the source or assessment tool from which they were derived, mainly STARS or UI GreenMetric. Finally,

category scores were calculated as the mean value of the normalized indicator scores within each category (Table 1).

Assigning Weight to the Indicators. The weight assignment was done through the playing-cards method. In total, eight stakeholders were identified. In this preliminary phase, the preferences of eight stakeholders were simulated using AI-generated stakeholder profiles. Therefore, the weighting process should be considered an exploratory step rather than the result of direct stakeholder engagement. To set the indicators in the stakeholders' order of preference, the stakeholders' average rankings for indicators were considered (Fig. 2). The ranks were then converted to a final consensus table, placing the indicators in an ascending order of importance. Based on the differences in average ranks, the following rule was applied:

- If the indicators had exactly equal ranks → they were placed in the same row, and were divided by + (shared ranking).
- If the difference > 1→ a white card was inserted between them. (Each one unit of difference was equal to one white card)
- If the difference ≤ 1→ indicators were placed successively without a white card. To compare indicators on a relative scale, the weights were also normalized to a sum of 100% (or 1).

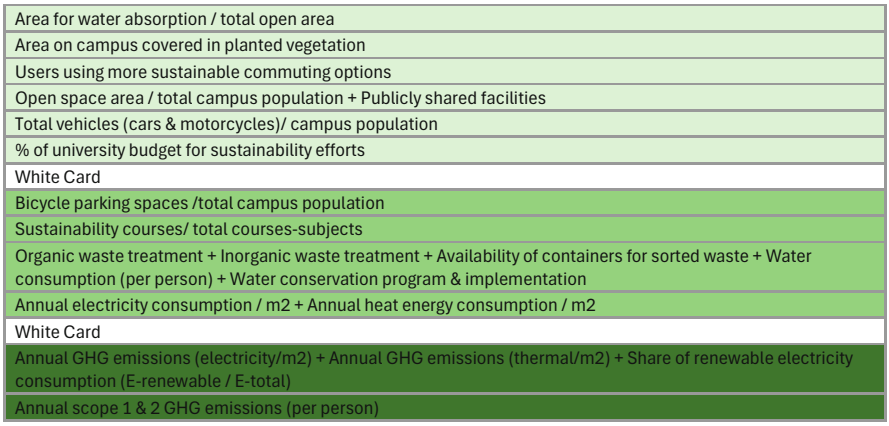


Fig. 2. Final consensus of implementation indicators

Current Performance Score of POLITO. The weight of each category is the sum of the weights of its indicators. The performance score in each category is calculated by multiplying the category's score by the category's weight. Finally, the overall sustainability performance score is obtained as the sum of all category performance scores divided by 100.

Future Scenarios. The next step focuses on improving the current situation. Based on a SWOT analysis, 10 actions were identified. As with the indicators, these actions were

ranked by AI-simulated stakeholders according to their preferences, and a Q-sort analysis [5] was then used to identify converging opinion trends. This process resulted in three future scenarios, each including the same ten actions arranged according to stakeholder preference. To reduce complexity, only the first three actions in each scenario, or the most representative ones, were selected for further analysis. For each future scenario, a feasibility assessment was then conducted to determine whether the proposed actions were feasible and to estimate the expected improvement in the corresponding indicators. Tables 2, 3 and 4 summarize these improvements.

3 Results and Discussion

3.1 Theoretical Results

Theme. Figure 3 shows the 138 thematically relevant studies according to SNTool's categories. Since most studies adopt a comprehensive approach in their assessment there is no significant difference among most categories. Still three categories emerge as the most addressed: Energy Climate Change Mitigation and Social Aspects aligning with two pillars of sustainability assessment topics: People and Planet. The third pillar economy however is the least regarded. Firstly because in comparison with education research or social involvement economy is not the priority of universities in general. Secondly since many of the Higher Education Institutions regarded are state universities their financial stability is guaranteed through the state budgets. Finally because there is no standard methodology to assess financial sustainability [6]

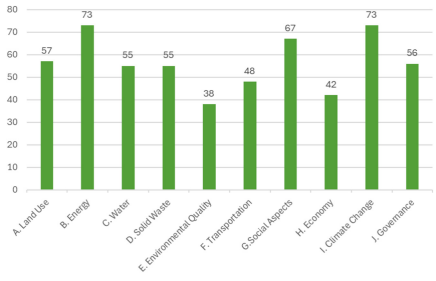


Fig. 3. 138 thematically relevant studies according to SNTool's categories

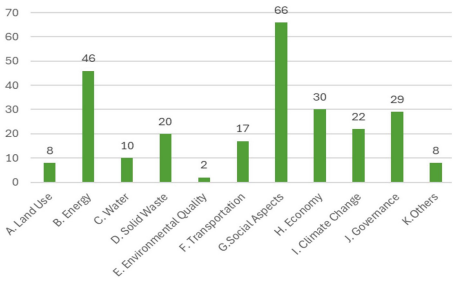


Fig. 4. 258 unique indicators according to SNTool categories

Indicators. Figure 4 illustrates the 258 unique indicators according to the SNTool's categories. It shows that "Social Aspects" and "Energy" account for the largest share. The surge in Social Aspects is due to a structural issue: campuses are not neighborhoods, and some campus-specific themes do not map neatly into urban categories [7, 8]. Similarly, in neighborhood-scale frameworks, such as SNTool, there is no specific category for academic and research-related aspects. Indicators, on the other hand, have been collected from campus sustainability studies, with many of them belonging to research-related

categories. These indicators are consequently classified under "Social Aspects", in addition to the original social indicators. The very small number of environmental quality indicators also suggests the same issue: environmental quality (e.g., particulate matter in the air) is considered essential in neighborhood/urban studies, but appears much less in campus studies, at least among the 44 studies reviewed.

3.2 Implementation Results

Table 1. Final list of 20 sustainability indicators

Category	Indicator	Performance Score	Low Benchmark	High Benchmark	Normalized Score	Normalized Weight	Category's Score	Category's Weight	Category weighted score
Use of Land	Area on campus covered in planted vegetation (%)	7.00	10	40	-1.0	0.88	-1	2.86	-2.86
	Open space area/total campus population (m^2 per capita)	4.3	10	70	-1.0	1.98			
Energy	Annual heat energy consumption (kWh per m^2)	51.77	130	50	4.9	7.27	2.65	23.35	61.96
	Annual electricity consumption (kWh per m^2)	57.88	180	30	4.1	7.27			
	Electricity-Renewable/Total (%)	6.15	10	30	-1.0	8.81			
Water	Water use (L/person/day)	16.09	54	14.5	4.8	5.73	3.65	11.46	41.83
	Water conservation program and implementation (%)	25	0	50	2.5	5.73			
Waste	Organic waste treatment (%)	100	0	85	5.0	5.73	4	17.19	68.76
	Inorganic waste treatment (%)	100	0	85	5.0	5.73			
	Availability of containers for sorted waste (n/1000m^2)	0.3	0	0.8	2.0	5.73			
Transportation	Bicycle parking spaces /total campus population (n/person)	0.03	0.01	0.07	2.3	3.96	3.98	7.92	31.52
	Total vehicles (cars & motorcycles)/total campus population	0.01	1	0.045	5.0	2.64			
	Users using more sustainable commuting options (points)	5.57	0	6	4.6	1.32			

Final Sustainability Score for the Current Situation. Table 1 shows a representative selection of the 20 final indicators, while the complete set was used in the assessment. The sum of all categories' weighted scores amounts to 328 points, which, when divided by the total weight (100), yields an overall score of 3.28 out of 5, representing POLITO's sustainability performance across the twenty indicators (Fig. 5).

Future Scenarios. Performing the Q-sort methodology on the actions, prioritized by the stakeholders, revealed three clear structures named as future scenarios. Tables 2, 3 and 4 summarize the first three actions in these scenarios and how they affect their corresponding indicators. The overall sustainability score for each scenario is shown in Figs. 6, 7, and 8, respectively.

Table 2. First future scenario, focusing on governance, investment, and long-term transition measures, represented mostly by institutional actors.

Actions	Annual electricity per m^2	Renewable electricity share	Containers for waste	Sustainability courses/total	GHG operations per person	GHG (electricity) per m^2
By 2030, double the PV share	−6.63%	100%			−5.6%	−8.7%
By 2030, increase the share of sustainability courses to 80%				26%		
By 2030, double the sorted-waste collection points.			100%			

Table 3. Second future scenario, focusing on users' daily needs and comfort, represented mostly by Students and Technical Staff.

Actions	Planted vegetation area	Bicycle parking spaces per capita	Users using more sustainable commuting options	Publicly shared facilities
By 2030, upgrade and expand campus facilities				63.2%
By 2030, double the share of green areas within the total open area	100%			
By 2030, enhance sustainable mobility: reducing daily trips by private cars to 0, increasing the bicycle parking spaces to at least 50%		50%	7.7%	

Table 4. Third future scenario, capturing minor differences as a secondary nuance rather than a fully distinct viewpoint.

Actions	Annual electricity per m^2	Renewable electricity share	Water use per person	Bicycle parking spaces per capita	Users using sustainable commuting	GHG operations per person	GHG (electricity) per m^2
By 2030, double PV share	−6.63%	100%				−5.6%	−8.7%
By 2030, 10% reduction in water consumption			−6%				
By 2030, enhance sustainable mobility				50%	8%		

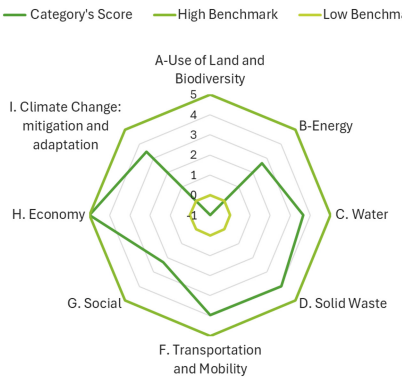


Fig. 5. Radar graph of the current POLITO's performance. **Score: 3.28**

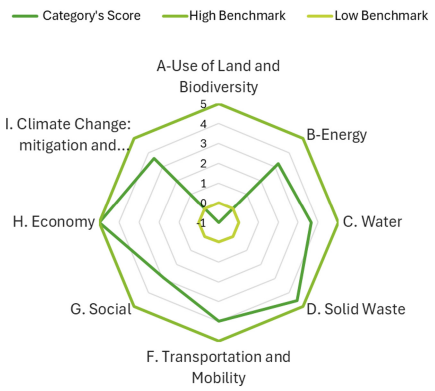


Fig. 6. Final assessment of the first Future Scenario. **Score: 3.58**

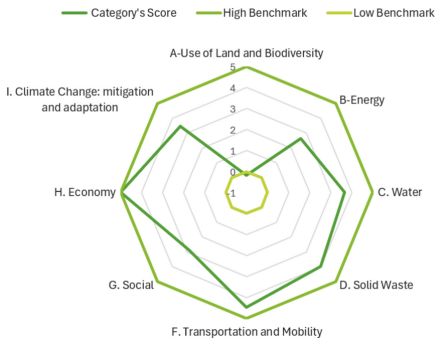


Fig. 7. Final assessment of the second Future Scenario. **Score: 3.37**

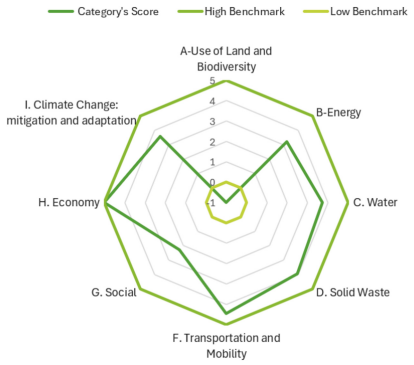


Fig. 8. Final assessment of the third Future Scenario. **Score: 3.48**

3.3 Discussion and Concluding Remarks

The results show that adapting sustainability assessment tools to university campuses requires more than transferring building- or neighborhood-scale indicators. Several campus-specific aspects, especially those related to education, research, participation, and everyday campus life, are not fully captured by existing SNTool categories. This confirms the need for a tailored framework for university campuses.

A limitation of this preliminary application is that stakeholder preferences were simulated through AI-generated profiles and were not collected through direct stakeholder participation. Future development of the framework should involve real campus stakeholders in the weighting and scenario-building process and test the proposed approach on other Italian university campuses.

Another limitation concerns the benchmark values, which were taken from the original assessment tools rather than calibrated specifically for the Italian or regional context. This limitation also highlights one of the main reasons for developing a campus-specific sustainability assessment framework: existing benchmarks are often available at the building, urban, or neighborhood scale, while university campuses represent a more specific institutional and spatial context that is not yet sufficiently covered by localized reference values. Future development of the framework should define locally adapted benchmarks for Italian university campuses.

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Demand-Responsive Transport (DRT) for Sustainable Rural Tourism: A Participatory Action Research Case Study in Latvia

Mara Grinberga-Silaua(✉), Dace Dance, and Sarmite Rozentale

Vidzeme University of Applied Sciences, Valmiera, Latvia
mara.grinbergasilaua@va.lv

Abstract. High dependency on private automobiles threatens ecological integrity and the transition to sustainable transportation in rural tourism, notably in Latvia's Gauja National Park. The economic inefficiency of fixed public transit and connection concerns creates a "mobility paradox" of unused infrastructure and dependence. Tourists also face major "last mile" connectivity problems. In a participatory action research (PAR) case study, 10 entrepreneurs from heritage manor hotels, beverage companies and nature conservation agencies participated between April 2025 and January 2026. Seven entrepreneurs found demand-responsive transport relevant to their companies, and the remaining three participated in the PAR process on transitions towards sustainable mobility and the circular economy. Within this partnership, sustainable growth is hampered by systemic logistical barriers, including empty movements, challenging planning and a lack of digital tools for SMEs. Authors propose Demand-Response Transport (DRT) to address these challenges. The goal is to combine minimal planned service provision with flexible, demand-oriented mobility by simulating infrastructure distribution using GIS-based data processing. The primary result is strategic recommendations through DRT, a publicly run, digitally enabled (PMDE) system that turns underutilised bus stops into valuable assets and removes barriers to SME collaboration. With synchronous logistics and digital gig-economy platforms, SMEs become active moderators of mobility, thereby making the system cost-effective. The study concluded that there is a need for a Regional Mobility Agency with a single digital platform to manage smooth booking and tracking, and to guide tourists toward sustainable "silent mobility" solutions

Keywords: Sustainable rural mobility · Demand-Responsive transport · Policy planning · Transport poverty · Active mobility

1 Introduction

The transition to sustainable mobility is a cornerstone of European rural mobility and nature tourism, as well as the European Green Deal; however, rural regions, such as Latvia's sparsely populated areas, including nature parks like Gauja National Park (GNP), face a significant "mobility gap" that threatens their ecological integrity [1,

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2]. This gap is a key driver of transport poverty, which, in the context of rural tourism and mobility, is defined as the inability of individuals—both tourists and locals—to access essential services, transport hubs, or employment opportunities due to a lack of affordable, reliable, or physically accessible public transport [3]. While urban centres have greater access to dense public transport networks, rural tourism remains heavily dependent on private vehicles, as traditional fixed-route public transport is not economically viable in Latvia's countryside and GNP. This situation creates a mobility paradox: visitors seeking "unspoiled nature" indirectly contribute to carbon emissions and noise pollution due to fragmented "last-mile" connectivity.

Studies and interviews with local small and medium-sized enterprises (SMEs) indicate that regional transport faces several systemic challenges. The "last-mile" problem stands out, as public transport routes often end several kilometres from the destination, necessitating additional private transport [4, 5]. A lack of information often compounds this physical barrier, as complex schedules make it difficult for modern tourists to navigate. Furthermore, infrastructure limitations, such as a lack of charging stations and "parking fees" for car-sharing in non-designated zones, hinder sustainable mobility. In terms of operations, SMEs observe inefficiencies, such as "empty runs", and lack the financial and human resources to implement digital tools, such as GPS tracking or AI-driven logistics, necessary for route optimisation.

The proximity of existing transport infrastructure, e.g., stations and stops, is often seen as a logistical obstacle rather than an advantage. This situation creates an unused competitive advantage for rural tourism service providers. To address these shortcomings, this study proposes a demand-responsive transport (DRT) strategy – a flexible, technology-based service that operates without fixed routes or schedules [6]. The study uses participatory action research (PAR) (a collaborative approach to inquiry that combines research, action, and education) with 10 tourism-related organisations to show how tourism operators can move from passive observers to active mobility enablers [7]. By demonstrating a possible "publicly managed, digitally enabled" (PMDE) model, this study outlines a collaborative problem-solving process, including coordinated transport and digital ride-sharing, that uses distance as a strategic advantage.

2 Context

The study was conducted as action-oriented research from April 2025 to January 2026. Its main objective was to assess the resources and processes that facilitate the transition to a circular economy and the Green Deal within the regional tourism system and tourism-related organisations. The organisations involved in the study represented various segments of the industry, including rural manor hotels, event organisation, and beverage producers who combine manufacturing with tourism. The study also included large-scale government agencies involved in nature conservation and environmental education, as well as the largest regional public transportation provider.

Through this initial study and interviews with rural SMEs, several systemic issues were identified that hinder regional mobility and are primarily related to the "last-mile" problem. In many cases, public transport routes end several kilometres before the final destination (Fig. 1), thereby forcing reliance on private transport and creating a "mobility gap" that threatens the region's ecological integrity due to a lack of connectivity. In

some areas, there are no taxis or similar services, which makes mobility without private vehicles even harder. A lack of information often exacerbates this physical barrier, as travellers find existing schedules too complicated or insufficiently tailored to facilitate travel without a car. Infrastructure constraints further hinder the transition to sustainable and active mobility; for instance, the lack of electric vehicle charging stations discourages "green" travellers; car-sharing users often incur additional costs because their destinations are not designated as official drop-off areas. Service providers face inefficiencies. That leads to unnecessary fuel consumption and emissions when picking up guests on extra rides. In addition, many organisations lack the financial and human resources to implement modern digital tools, such as GPS tracking and AI-driven logistics, which are necessary to optimise regional routes and reduce the environmental impact of rural tourism.

3 Literature Review

The theoretical framework explains the transition from traditional, high-capacity infrastructure and services to a flexible, decentralised network designed to address specific logistical challenges in sparsely populated rural areas. This transition is grounded on the last-mile theory, which states that the main obstacle to sustainable travel is the separation between transit hubs and destinations [4, 5]. In rural settings, this gap often leads to transport poverty, defined as the systematic inability of individuals to access essential services or destinations due to a lack of affordable and reliable transport options [3, 8]. This theory explains why tourists in the Gauja National Park (GNP) rely on private vehicles, as the current fixed-route system remains economically disadvantageous for both service providers and users. To address these challenges, the study uses the demand-responsive transport (DRT) paradigm, which is based on a flexible, technology-driven approach with no fixed routes or schedules. As supported by the DRT theory, this approach enables the development of a model that transforms underused infrastructure, such as bus stops, into functional assets by dynamically directing smaller vehicles only when needed, achieving cost efficiencies where traditional routes have not been cost-effective [6, 9].

The Resource-Based View (RBV) of the firm anchors the solution of SMEs, transforming passive stakeholders into active mobility moderators. RBV management theory states that firms achieve sustainable competitive advantage by acquiring and utilising internal resources that are Valuable, Rare, Inimitable, and Organised (VRIO) [10–12]. In this study, SMEs apply strategic agency to manage the "last mile", converting physical distance into a competitive asset by internalising guest transport logistics. Finally, the framework integrates sharing economy principles that allow a diverse cross-section of stakeholders to leverage localised resources, such as community drivers, through platforms like Abillio, where freelancers could more easily and legally be paid for their services, to bridge connectivity gaps without the high capital costs of private fleet ownership [13, 14]. While the primary focus remains on connectivity and agency, this framework allows for the future integration of the Energy Loop model, where decentralised renewable energy could eventually fuel electric mobility to guarantee long-term operational resilience in GNP or similar areas [15, 16].

4 Methodology

The study focuses on the Gauja National Park (GNP) area, particularly investigating the operational integration of tourism SMEs, including hotels, cafes, and museums.

The methodology was structured into three levels to address challenges identified by the entrepreneurs:

1. Qualitative Engagement (PAR): At this stage, the primary focus was on helping organisations see the transition from structural passivity regarding transport constraints to strategic agency. By taking control of transportation in-house, SMEs were able to address the "last-mile" problem and the lack of tailored information by creating their own "travel prescriptions" for guests. Data were gathered using two complementary methods across all 10 tourism-related organisations from April 2025 to January 2026. The first involved a structured survey instrument on organisational sustainability practices across thematic blocks, including waste management, water use, energy, transport, green investments, circular economy readiness, and biodiversity. Second, in-person semi-structured interviews were conducted with organisational representatives to deepen and contextualise survey responses. Qualitative and quantitative data were analysed using a structured coding framework based on two analytical dimensions. Responses were initially categorised according to the business processes defined as data entry points for each organisation. Second, responses were assessed on five circular economy characteristics: (1) resource efficiency, (2) supply chain transparency, (3) product and service life extension, (4) waste prevention, and (5) system-level innovation. This two-dimensional matrix enabled a systematic comparison of organisational practices across entrepreneurs and the identification of both barriers and enablers of circular, sustainable mobility. Conclusions were drawn through interpretive synthesis, by cross-referencing the coded qualitative findings with the quantitative spatial and financial modelling results described in steps 2 and 3 below.
2. Quantitative spatial analysis: Using geographic information system (GIS) data, the study modelled the distribution of underused public transportation infrastructure to identify where the "bridge" between high-capacity hubs and destinations was missing.
3. Socio-technical modelling: To address the shortage of financial and human resources, stochastic financial modelling was used to assess the feasibility of utilising third-party digital platforms, such as Abillio. The results indicate that freelancers could be a missing part of the model, and the economic model can provide the necessary digital tools and tax compliance without the additional costs of traditional employment.

5 Results

The results of this study indicate a significant shift in the functional role of rural tourism SMEs, which are transforming from passive observers of transit restrictions into active promoters of mobility. By implementing "last-mile" control, these organisations effectively take over the final part of the guest's journey. This solution is achieved by implementing demand-driven transport services that are coordinated with the company's existing logistics—such as supplier procurement or employee shifts—thereby reducing "empty runs" and maximising resource efficiency. "Last-mile" control can be

influenced by entrepreneurs, who cannot change state policies but can improve local transport. As shown in the spatial analysis of the region (Fig. 1), the basic infrastructure for this multimodal transition already exists; however, the most significant shortcoming is not coverage but rather intermodal connectivity. Specifically, there is a critical need to improve signage and information and ensure a seamless physical transition from major transport hubs to tourist routes, such as Mežtaka, which is part of the European long-distance hiking route E11 [17]. The results show that offering specific "travel recipes", such as predetermined train and minibus departure times, reduces the psychological barrier caused by rural isolation and significantly improves car-free travel.

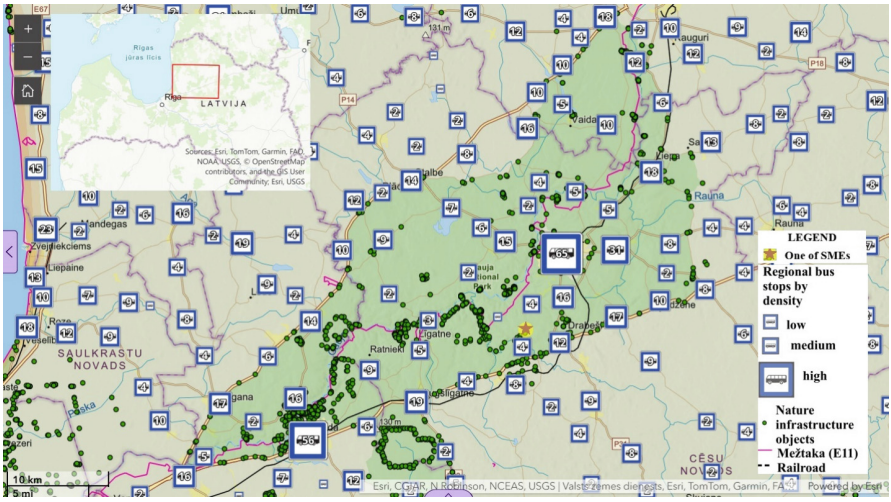


Fig. 1. Map of Gauja National Park public transport infrastructure and natural objects. Source: M.Grīnberga-Šilaua, cartographer M.Ķibers, 2025

The study showed that a collaboration and car-sharing model is essential for reducing the capital investment required to establish a fleet of specialised vehicles. The seasonal minibus route, which operates from May to September, has been recognised as an effective solution when costs are shared among a network of local businesses. Localised sharing economy is further facilitated by digital service economy platforms, such as "Abillio", which allows SMEs to legally hire individuals as on-demand drivers while complying with tax requirements and avoiding the complexities of traditional employment. Digital integration is a significant factor of this connectivity, using QR codes for instant access to schedules, event-specific ride-sharing platforms, and Google Maps to simplify the tourist experience. This is supported by other research indicating that psychological factors, such as perceived ease of use and behavioural control, are fundamental drivers in the successful adoption of pro-environmental mobility choices [18]. Strategic partnerships with shared mobility service providers, such as Bolt Drive and CityBee, further enhance the ecosystem by providing official drop-off zones, effectively reducing the need for private vehicles in the region.

6 Discussion and Conclusion

The study demonstrates that the mobility gap in rural protected areas, such as Gauja National Park, is not a geographical barrier but rather a logistical one that can be overcome through SME-led initiatives. Based on the theory of competitive advantage and the resource-based view, this model demonstrates that integrating transport management within organisations enables them to achieve outstanding sustainability results. By transitioning from passive observers to active mobility facilitators, tourism service providers can turn physical distance into a competitive advantage. This transition demonstrates that demand-responsive transport (DRT) offers a viable alternative to the current car-centric tourism dilemma. As indicated by the infrastructure mapping in Fig. 1, the presence of an existing but disconnected network suggests that the main problem is the lack of a "bridge" between high-capacity transit hubs and destinations along nature trails. The effectiveness of this strategy relies on the collaboration between social responsibility and digital innovation.

For instance, platforms such as "Abillio" reduce high labour costs by engaging the local community, thereby creating a more flexible and accessible workforce. Ultimately, the psychological transformation of tourists is closely linked to the issuance of "travel prescriptions", which give visitors the confidence they need to opt out of private vehicles in favour of the park's quiet mobility. The proposed publicly managed, digitally enabled (PMDE) system offers a scalable governance model in which regional bodies act as mobility coordinators to promote these seasonal "quiet mobility" routes. While the primary focus remains on connectivity and digital coordination, the energy cycle model is recognised as a potential future driver of sustainability by reducing long-term energy costs. Looking ahead, future implementation should prioritise the expansion of zero-emission protected areas models. In these models, transportation serves both as a logistical necessity and as an enjoyable, sustainable service that enhances the nature park's overall ecological integrity. Ultimately, sustainable circular transport is a key component in rural and urban areas and must be prioritised more strongly to ensure long-term resilience and environmental balance, not only in the context of natural resources but also in social aspects, to establish a human-oriented system.

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Use of Emissions Control Indicators as a Tool to Guide NZEB Carbon Retrofits in Brazilian Public Universities: A Case Study

Natália Galvão dos Santos(✉), Mauricio Carvalho Ayres Torres, and Ruane Fernandes de Magalhães

Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
arq.nataliagalvao@gmail.com

Abstract. In view of the global warming trend and the increase in CO_2 emissions, largely driven by the construction sector, the development of low-carbon strategies for buildings has become increasingly urgent, such as the nZEB carbon trend. This need is particularly pronounced for existing buildings, where extending service life through environmentally responsible retrofit solutions plays a key role in emissions reduction. Among building typologies, Higher Education Institutions (HEIs) present specific challenges due to their functional complexity, high occupancy levels, and stringent comfort requirements, particularly in the public sector. *Low-carbon* indicators for retrofits were developed to monitor and control emissions. This research adapt an existent management method, with fifteen indicators for monitoring and controlling CO_2 emissions in public buildings, through a case study of a public HEI in Brazil, aiming to simplify the decision-making process, typically based on life cycle assessments, which are often complex and time-consuming The study proposes a framework that reallocates responsibility for decarbonization from individual designers to university management, thereby democratizing knowledge, strengthening institutional governance and refining the original method to reflect the context of Brazilian public HEIs better. The indicators are used to structure a systematization of low-carbon management within the university. The proposed framework indicates a high potential for a medium to long-term transition towards low-carbon and circular practices within the university. Furthermore, it highlights the effectiveness of involving professionals, students, and stakeholders not traditionally engaged in retrofit-related decision-making, positioning the university as a living laboratory and integrating emissions management into institutional processes

Keywords: Educational Public Buildings · Sustainable Transition · Low-Carbon Retrofitting · Management Strategies · Resource Efficiency

1 Introduction

The construction sector is a major contributor to global CO_2 emissions and energy consumption. In 2023, buildings accounted for 32% of global energy demand and 34% of CO_2 emissions, with operational emissions reaching 9.8 Gt and embodied carbon

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around 2.9 Gt [11]. In response, increasing research has focused on strategies to mitigate emissions, among which sustainable retrofitting stands out as an effective approach to reducing greenhouse gas emissions and climate impacts [7].

This challenge is particularly relevant for Higher Education Institutions (HEIs), which comprise large and complex building stocks with diverse functions such as classrooms, laboratories, libraries, and service areas. Their high occupancy density, strict comfort requirements, and extended operating hours make campuses important targets for energy efficiency and carbon reduction initiatives [5, 13]. In Brazil, the higher education system includes hundreds of institutions, many operating large campus infrastructures that resemble small urban systems [10].

Several Brazilian universities have already implemented sustainability initiatives, including carbon inventories, institutional sustainability plans, renewable energy projects, and research programs focused on low-carbon strategies. However, managing emissions in university buildings still requires structured decision-making tools capable of guiding retrofit processes, which should be easy to use, unlike the more well-known tools, which require specific knowledge and only one team in charge, as Life Cycle Assessment. To deal with it, Liu [8] developed a methodological framework with 15 measures to guide carbon reduction in public buildings, based on sustainability certification criteria and emission-control indicators to support retrofit planning, while there is no focus especially on HEIs, nor a clear division of responsibilities.

In this context, the study evaluates the applicability of Liu's framework to a public HEI in Brazil through a case study at the Federal University of Rio Grande do Sul (UFRGS), aiming to develop indicators that distribute decarbonization responsibilities between designers and university management.

2 Method

2.1 Case Study Context

The Faculty of Architecture and Urban Planning (FAU) of UFRGS, inaugurated in 1958, is one of the oldest and most qualified institutions for teaching architecture and urbanism in Brazil [12]. For several years now, the course has included subjects in sustainability and environmental education, aiming to increase skilled professionals in these areas. Despite the interest in the school curriculum, the HEI has not yet undergone improvements to meet sustainability and environmental metrics.

Considering the operation of universities and the constant need to adapt spaces to accommodate new demands, this work will focus on adapting an existing framework for carbon emissions control, aiming to distribute decision-making responsibilities, democratizing knowledge on the subject, and favoring process control by stakeholders who are naturally involved for longer in the context of the building. Additionally, the study seeks to systematically understand the main metrics to be adopted within the chosen scope and evaluate their replication for other public HEIs in Brazil, with a view to proposing a useful tool for retrofits of various kinds within the context and making the university environment a true living laboratory.

2.2 Regulatory and Normative Framework

The management of public educational institutions in Brazil is governed by federal legislation and institutional regulations. The Federal Constitution of 1988 grants universities administrative and financial autonomy, although they remain subject to public administration rules. Law No. 14,133/21 establishes national procedures for public procurement, including the possibility of performance-based remuneration linked to quality and environmental sustainability criteria.

At the institutional level, universities operate through statutes, regulations, and management plans, which must comply with national standards such as the Normative Instruction for the Energy Efficiency Class of Commercial, Service, and Public Buildings (INI-C). The INI-C establishes the methodology for assessing the energy efficiency of new public buildings, including envelope, lighting system, HVAC, water heating, renewable energy generation, and efficiency indicators [6].

Although policies promoting sustainability exist in public HEIs, their implementation remains limited due to barriers such as high initial costs [13], bureaucratic complexity arising from fragmented policies [2], and insufficient awareness or training among professionals regarding performance targets [9]. These challenges highlight the need for additional measures to strengthen sustainability-oriented actions through an analytical framework for decision-making assessment.

Based on a review of research related to decarbonization in existing public and institutional buildings, which mainly includes studies that propose a deeper analysis of the building life cycle [1, 5, 9] and energy simulations [3, 4, 13], we chose to work with a simplified tool focused on sustainability indicators, proposed by Liu et al. [8]. The aim is to simplify decision-making to reduce carbon emissions in public buildings as a method for devising strategies for the case study.

The tool is divided into six scopes: materials, energy, management, innovation, location, and water, comprising 15 measures (Table 1). It was developed by cross-referencing and summarizing CO_2 emission control indicators from international databases to build a framework that meets different needs worldwide, comparing the indicators characteristics of the following certifications: LEED (USA), BREEAM (United Kingdom), GM (Singapore), and ASGREB (China). Within the certifications, each measure has a different weight, according to its relevance, and the maximum score in Liu's [8] framework is 84.2%, as it is based on systems that also address other aspects of sustainability beyond carbon emissions control, totaling 100%.

To improve the method's efficiency, the decision-making process at FAU will be evaluated, and a reorganization will be proposed to increase flexibility in applying the method and partially reduce project bureaucracy, in addition to developing an inventory framework to support the standardization proposed by the method. This measure aims to simplify decarbonization tools and streamline decision-making, which currently operates as shown in the Fig. 1.

Table 1. Summary of scopes and measures. The sum of the weights is equal to 84.2%, accounting for the maximum score of the framework. Source: Adapted from [8].

Scope	Mandatory measures	Recommended measures	Scope weight
Materials	Safety and durability	–	18,3%
	Waste recycling		
	Material Location		
	Green materials		
Energy	Energy saving in buildings	Use of energy from renewable sources	17,7%
	Energy saving of equipment		
Management	Intelligent operation	Political and institutional orientation	14,9%
Innovation	Calculation of carbon emissions in the building	–	14,9%
	Historical and cultural heritage		
Location	Low-carbon transportation	Reduction of the heat island effect	10,5%
Water	Reduced consumption	Non-traditional water use	7,9%

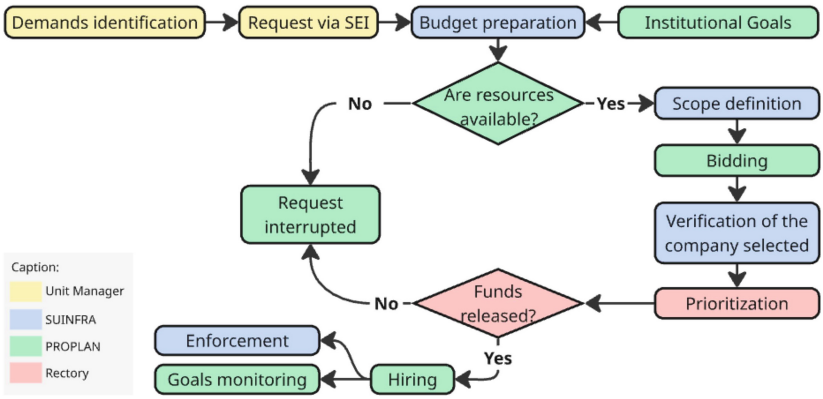


Fig. 1. Flowchart of the current decision-making structure. Source: Developed by author.

3 Results and Discussions

3.1 Indicator Assessment across Management Domains

Based on the application of Liu's [8] model to the FAU UFRGS case study, the results were translated into an adapted framework presenting decision priorities at project and management levels. The framework supports both building users and designers in making

informed decisions that can be maintained throughout the bidding process. This organization helps identify not only estimated environmental impacts, but also the institutional constraints affecting implementation.

The scopes in Table 1 were reformulated by the author to find decarbonization opportunities, including items within each measure (in italics), with scores equally redistributed for each of them (in bold), and it is mandatory to comply with at least one item within each of the mandatory measures, as summarized in Table 2. The safety measure was excluded from the scope because it is not directly related to decarbonization.

Table 2. Measures adapted to the case study. The weights are estimated to scope sum (Table 1). Source: Developed by author.

Mandatory measures	Recommended items (at least 1 item by each measure)	Weight
Durability	*Materials durability* (1)	**4,575%**
Waste recycling	*Prioritize materials that have been produced through recycled raw material* (2)	**4,575%**
Material Location	*Prioritize materials for shorter distance, not exceeding 500 km* (3)	**4,575%**
Green materials	*Prioritize materials that are or have reusable or recyclable packaging* (4)	**1,525%**
	Prioritize brands that have reverse logistics (5)	**1,525%**
	Prioritize materials with abundant raw materials in the region (6)	**1,525%**
Energy saving of buildings	*Prioritize equipment with an A grade in the PROCEL seal* (7)	**8,85%**
Energy saving of equipment	*Carry out equipment operation plans, involving students and employees of the HEI* (8)	**8,85%**
Intelligent operation	*Installation of IoT (Internet of Things) elements and equipment* (9)	**3,725%**
	Smart glazing in all build (10)	**3,725%**
	Installation of presence sensors (11)	**3,725%**
	Automatic stand-by mode equipment (12)	**3,725%**
Calc. of emissions	*Hiring of specialized staff* (13)	**7,45%**
Historical and cultural heritage	*Maintain a team specialized in historical heritage* (14)	**3,725%**
	Involve HEI users in reform decisions (15)	**3,725%**
Low-carbon transportation	*Installation of paracycles in IES* (16)	**2,625%**
	Policies to encourage the use of low-carbon transport (17)	**2,625%**
	Inclusion of building users in decision-making for incentives (18)	**2,625%**
	Constant improvement of universal accessibility on campus (19)	**2,625%**
Reduced water consumption	*Installation of water-saving elements* (20)	**3,95%**
	Creation of consumption reduction policies (21)	**3,95%**

Regarding the measures recommended by Liu [8], this research allows the inclusion of additional sustainability measures when there is a link between maintenance inputs and project specifications. The University score will not have a minimum score, as the aim is to promote nZEB carbon retrofits. Instead, the focus is on gradually increasing the number of measures over time, according to local feasibility, ensuring continuous improvement in the HEI's score, preventing setbacks, and maintaining results for up to four consecutive years, corresponding to the average rectoral administration term.

3.2 Implications for Retrofit Decision-Making

Renovation requests at the University follow a hierarchical decision-making process involving multiple stakeholders. Currently, decisions are made through a bottom-up system with limited involvement from university administration and bureaucratic procedures that may halt projects even after completion, overburdening the infrastructure department, as shown earlier in Fig. 1.

Thus, effective decarbonization in public HEIs requires not only technical and environmental performance but also compatibility with purchasing processes, standardization of specifications, and logistics, ensuring operational viability and continuity over time. However, there are still barriers that compromise this relationship, such as budget, bureaucracy, or human resources.

Lean Governance advocates reducing bureaucratic waste to optimize workflows, accelerate decision-making, and improve responsiveness to institutional demands [2]. In this context, implementing decarbonization measures requires streamlining bureaucratic processes and reducing the number of actors involved in decision-making, facilitating coordination and improving control over retrofit actions in public HEIs. To support the replicability of this study, a proposed organizational flow for retrofit projects in public higher education institutions is presented below (Fig. 2).

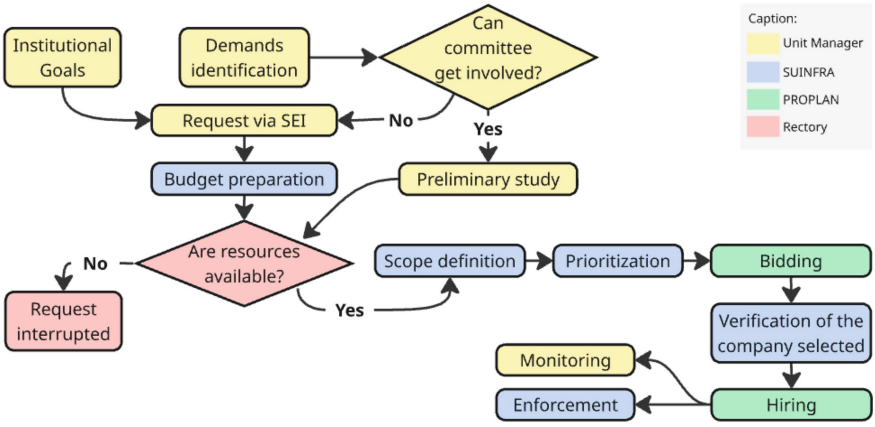


Fig. 2. Flowchart of the proposed decision-making structure. Source: Developed by author.

Under the proposed new decision-making structure at FAU, each department involved will have its responsibilities allocated as described below:

1. **Unit Manager:** Institutional demands should be organized and supported by internal policies that promote user awareness and guide sustainability act ions. (Table 2, items 8, 15, 18, 21);
2. **PROPLAN:** Mediates bids and legal procedures without getting involved in technical aspects or decision-making that requires specific knowledge;
3. **SUINFRA** Conducting inventories, developing projects, prioritizing demands, and supervising construction works, while ensuring compliance with decarbonization measures, guaranteeing standardization and alignment with sustainability requirements (Table 2, items 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 16, 20);
4. **Rectory:** Creates public policies for decarbonization, ensures the necessary human resources for their implementation, and coordinates the funds available for maintenance and renovations (Table 2, items 13, 14, 17, 27, 19).

Implementing bottom-up decision-making in HEIs requires organizational change, but it can reduce bureaucracy, strengthen stakeholder engagement, and improve trust. Integrating decarbonization decisions before retrofit interventions also encourages user involvement with the built environment. In this context, renovation commissions are essential to involve students in institutional decision-making and experimentation, especially in architecture schools, where innovative solutions can later inform practice, teaching, and institutional policies.

For the measures mentioned to be appropriate to the FAU context, it is very important that the university management, together with the technicians, conduct a comprehensive inventory of all relevant aspects of the site to the proposed framework. This document should be updated periodically and cover the university's environments and their current uses, as well as the state of each construction system that makes up the site, the equipment that integrates these areas, their uses and maintenance, and events that may have caused degradation at the site, as shown in Fig. 3, in order to obtain a better perspective for the decision to standardize future purchases.

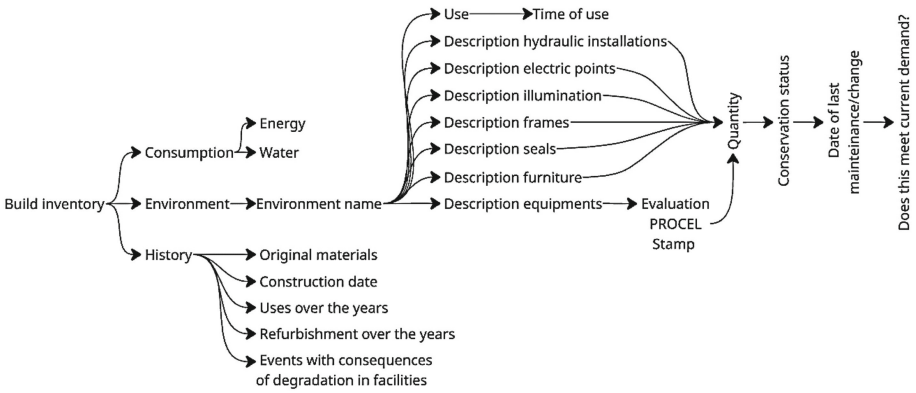


Fig. 3. Inventory proposal for HEIs low-carbon retrofitting. Source: Developed by author.

4 Conclusions

By adapting Liu's [8] tool, it was possible to develop a progressive decarbonization plan that enables HEIs to establish benchmarks and targets for specific scores. Revising the university decision-making process also helped reduce bureaucracy in renovation demands, empower building users, and reduce the workload of the infrastructure sector. The proposed organization is promising due to its easy replication across public HEIs, which often share similar administrative structures.

The inventory model further improves internal facility management by incorporating data such as energy and water consumption and construction materials. This tool supports future decarbonization metrics and enables simplified comparisons between existing conditions and renovation proposals.

Another important contribution is the creation of a culture of sustainable responsibility among students, staff, and faculty through their participation in building-related decisions. In this context, the renovation committee plays a key role, especially in architecture schools, where innovations can be tested and later disseminated through university practices, teaching, and internal policies. However, given the current asset management structure at UFRGS, transferring sustainability and decarbonization decisions directly to building managers remains complex, requiring a holistic approach at the university level.

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Advancing the Adaptive Reuse Potential Model: A Multi-criteria and Impact-Based Assessment Across Urban Context

Debora Anelli[1](✉), Francesco Tajani[1], Marta Braulio-Gonzalo[2], João Zambujal-Oliveira[3], and Pierluigi Morano[4]

[1] Department of Architecture and Design, "Sapienza" University of Rome, Rome 00196, Italy
debora.anelli@uniroma1.it
[2] Department of Mechanical Engineering and Construction, Avda. Vicent Sos Baynat, s/n 12071, Castellón de la Plana, Spain
[3] NOVA LINCS (FCT) | University of Madeira (FCS), Funchal, Portugal
[4] Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, Bari 70126, Italy

Abstract. Adaptive reuse of existing buildings is a needed strategy for reducing resource consumption and improving the sustainability of the building. However, many evaluation models adopted in decision-making processes are based only on characteristics of properties, relying on static representations of obsolescence and providing limited support for evaluating the effects generated by the reuse on surrounding urban context. The aim of the work is to propose a methodological framework for assessing adaptive reuse potential based on relevant obsolescence categories and including the potential impacts generated by the intervention of reuse. The proposed framework is structured into two modules: the first one, is intended for determining the intrinsic potential of the abandoned building through Analytic Hierarchy Process (AHP) weights system of obsolescence indicators; the second one, is aimed at assessing (ex-ante) the impacts that could be generated on neighborhoods. The study contributes an original two-module decision-support framework combining building reuse potential and ex-ante urban impact assessment. Through multidimensional indicators and AHP weighting, it improves transparency and traceability in circular adaptive reuse evaluation for supporting optimal and efficient circular economy's decisions. Future developments will concern the application of the proposed framework into a real case study by testing the validity of results with the comparison of compensatory and non-compensatory multicriteria techniques

Keywords: adaptive reuse · multicriteria decision analysis · sustainability assessment · urban regeneration · circular indicators

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1 Introduction

Adaptive reuse of existing buildings is recognized as a strategy for promoting sustainability in the built environment. In contrast to demolition and new construction, adaptive reuse substantially reduces material consumption, embodied energy, construction waste, and land-use pressure, often avoiding 50-75% of embodied carbon emissions by preserving carbon-intensive structural elements like foundations, frames, and envelopes [1]. It also diverts substantial materials from landfills by minimizing demolition activities, considering that construction and demolition waste represents around 38–40% of total waste generation in the EU and similar shares globally [2]. Within the circular economy paradigm, and under the umbrella of the European Union (EU) Circular Economy Action Plan, adaptive reuse is increasingly recognised as a key strategy to transform the construction value chain and to reduce the sector's environmental impacts. Beyond environmental benefits, adaptive reuse supports social inclusion, urban regeneration and value creation within existing urban fabrics, reinforcing its role in achieving circular and climate objectives at building and neighbourhood scales. In this context, robust assessment models capable of capturing circularity, impacts and risks of adaptive reuse interventions are essential to support evidence-based decision-making. Despite the growing recognition of adaptive reuse as a sustainable and circular strategy, decision-makers still face challenges in prioritising reuse interventions within complex urban systems. Existing assessment approaches often focus on building-level characteristics while overlooking broader socio-economic, cultural and environmental impacts on the surrounding neighbourhood. Furthermore, the lack of transparent indicator systems limits the replicability and implementation of many existing tools. Addressing these gaps requires integrated, multi-criteria and impact-based approaches aligned with circular economy policies and sustainability assessment frameworks [3]. This paper develops a multi-criteria framework for assessing adaptive reuse potential of buildings, aiming to enhance the importance of evaluating the potential impacts on the surrounding neighbourhoods through decision-making transparency. The approach focuses on three key aspects: first, it suggests the use of an obsolescence dashboard system by defining environmental, social, cultural, and economic (ESCE) level of obsolescence; second, it takes into account through Analytic Hierarchy Process (AHP) the relevance of obsolescence into the determinants of useful life of abandoned buildings; third, it creates analysis of impacts according to different isochrones and scenarios intervention of reuse. The remainder of the paper is as follows: Section no.2 describes each step of the proposed framework; Section no.3 concerns main pros and cons of the work and its future directions with a real case study application.

2 Methodology

2.1 Framework Overview

The proposed framework builds upon previous developments of the Adaptive Reuse Potential Index (ARPI) model proposed by Anelli et al. [4] and inspired by Langston's Adaptive Reuse Potential (ARP) model [5, 6]. The contribution of the paper is an operational extension of previous ARP-based approaches, structured in two modules to estimate: (A) the intrinsic potential for reuse of an existing building through a dashboard

of obsolescence indicators, with their relevance objectified via the AHP (e.g., as applied in related multicriteria adaptive reuse assessments [7, 8]; and (B) an Ex-ante Impact Potential (EIP), designed to assess potential impacts in the urban environment associated with alternative reuse scenarios, while keeping the intrinsic component distinct from the territorial impact component (aligned with ex-post/ex-ante impact evaluations and multidimensional extensions in heritage reuse frameworks [9]).

In summary: Module A returns a synthetic measure of the "intrinsic reuse potential" of the asset; Module B, applicable only after the ARP estimation, allows to compare scenarios in terms of potential impacts in the Area of Influence (AoI) defined by isochrones. Figure 1 depicts the workflow of the proposed methodology.

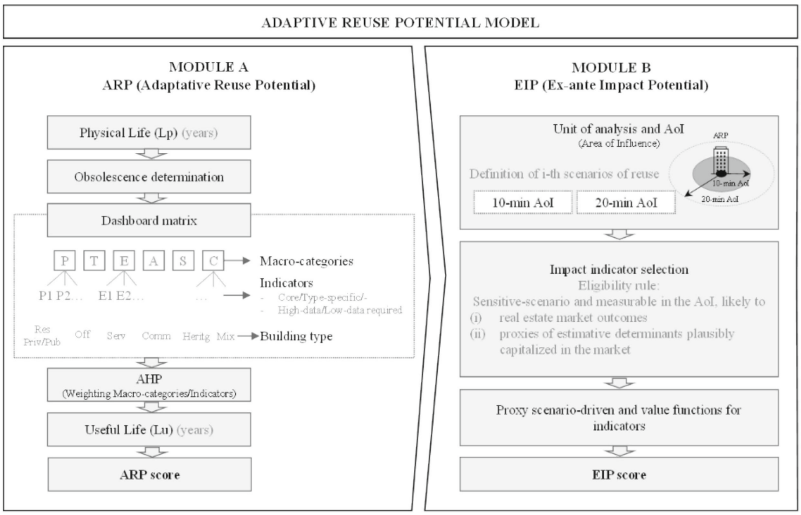


Fig. 1. ARP Model proposal of methodological framework.

2.2 Module A—ARP

2.2.1 Physical Life Assessment

In continuity with the model developed in Anelli et al. [4], the estimation of the physical life *Lp* is carried out by means of an improved physical life worksheet that compares the conditions of the context and the robustness of the asset for the purposes of the expected physical life. The result is expressed in years and constitutes input for the estimation of the useful life.

2.2.2 Obsolescence Dashboard: Core vs. Type-Specific Indicators

The determination of obsolescence is broken down into six families consistent with the literature on adaptive reuse and building obsolescence: Physical (P), Technological/Functional (T), Economic (E), Environmental (A), Social (S), Cultural/Heritage (C).

To ensure replicability and transferability to different uses, the dashboard is structured as a matrix of indicators × building types, distinguishing:

- Core set (Cr): essential and applicable to most types;
- Type-specific set (Ts): depending on the intended use (residential private/public, offices, public services, commercial/hospitality, mixed-use; with heritage module when relevant).
- (−): non-priority in the minimum dashboard

Each macro-category can be operationalized with a Primary measure (more informative) and a Proxy measure (low-data), associated with a level of "data effort/availability" -low (L) or high (H). Below is an excerpt from the dashboard (Table 1):

Table 1. Excerpt of dashboard matrix of obsolescence indicators.

Cat.	Obsolescence indicators	Building typology							Source
		Res-Priv	Res-Pub	Off	Serv	Com	Her	Mix	
P	Envelope/structure status	Cr	Cr	Cr	Cr	Cr	Cr	Cr	[10, 11]
T	Functional adequacy of layout/spaces	Ts	Ts	Cr	Cr	Cr	Ts	Cr	[11–14]
E	OPEX	Cr	Cr	Cr	Cr	Cr	Cr	Cr	[10, 11, 13]
Env	Operating CO_2 / emissions ($kgCO_2e/m^2a$)	Cr	Cr	Cr	Cr	Cr	Cr	Cr	[13, 14]
S	Accessibility/barrier-free	Cr	Cr	Cr	Cr	Cr	Cr	Cr	[13, 14]
C	Integrity, constraints, compatibility of use	–	–	–	–	–	Cr	–	[12, 14]
[…]									

2.2.3 AHP-Based Weighting of Obsolescence Macro-Categories

Previous applications of ARP-based approaches demonstrated the usefulness of multi-criteria methods for identifying adaptive reuse priorities in urban contexts [4, 15, 16]. In the present work, the choice to weigh the obsolescence categories is formalized to replace Langston's assignment by range (0–0.20) with a transparent and verifiable procedure. Let $k = 1,2... k$ the set of obsolescence macro-categories (P, T, E, A, S, C). A matrix of pairwise comparisons is constructed using the Saaty scale based on expert judgments, and the weight vector is obtained as the principal eigenvector (or, alternatively, by means of a normalized geometric mean). The consistency of the judgments is verified through the Consistency Ratio (CR). When quantitative indicators are used, the pairwise comparison matrix is instead constructed based on the ranking of their values. In this case, the implied transitivity ensures that the consistency requirement is always satisfied. The resulting weights are then used to aggregate the indicators (core and type-specific) into a synthetic measure of overall obsolescence.

2.2.4 Useful Life

The useful life *Lu* is calculated as "discounted physical life", according to the Langston-based approach already adopted in Anelli et al. [4]:

$$Useful\ life = \frac{Physical\ life}{1 + \sum_{i=1}^{n} O_i} \tag{1}$$

where $\sum_{i=1}^{n} O$ represents the overall annual rate of obsolescence deriving from the aggregation (weighted) of the obsolescence households. Unlike Langston's range approach, in this paper $\sum_{i=1}^{n} O$ is obtained by combining: (i) indicator scores for each macro-categories (core/type-specific) and (ii) weights *wk* from AHP.

2.2.5 ARP Score

The ARP score is then calculated as a function of the *ELu* and the effective age of the building, *ELb,* according to the formula:

$$ARP\ SCORE = \frac{\frac{100 - ELu^2}{100 \cdot ELb}}{ELu} \tag{2}$$

In the setting proposed here, ARP is a building-intrinsic output: it returns a synthetic measure of the potential for reuse of the asset regardless of the scenario and the surrounding context and is used as an ex-ante "filter/priority" to decide whether the building is a candidate for further scenario-based analysis (EIP, module B).

2.3 Module B—Ex-ante Impact Potential (EIP)

2.3.1 Unit of Analysis and AoI Definition Through Isochrones

The unit of analysis of Module B is the i-th scenario of reuse of the building whose calculation of the reuse potential is expressed by ARP score. The Area of Influence (AoI) is set ex-ante to ensure comparability between scenarios: a 10-minute pedestrian isochrone (alternately buffer 700–800 m) is assumed as the main AoI for proximity impacts; a secondary AoI (20 minutes or ~1.5 km) can be used for sensitivity analysis or more common impacts. The time horizon is defined in a way that is compatible with the ex-ante nature: short (1–3 years) and medium term (4–10 years), where necessary.

2.3.2 Impact Indicator Selection Rule: Intervention Sensitivity and Real Estate Market-Mediated Relevance

To ensure that the assessed impacts reflect the changes plausibly induced by the intervention, the EIP protocol imposes a scenario-sensitive selection rule based on a minimum causal chain: scenario → output/services → proxy impact mechanism measurable in the AoI. In this contribution, in line with the evaluation approach, the eligibility of the indicators is further linked to a market-mediated relevance: indicators are selected that constitute (i) real estate market outcomes (e.g. potential changes in prices/rents, vacancy, liquidity) and (ii) proxies of estimative determinants plausibly capitalized in the market

(e.g. accessibility/amenities, perceived environmental quality, safety/supervision, footfall), provided that they are sensitive scenario and measurable in the AoI. Formally, for a Si scenario, the EIPSi set is defined as a J subset of candidate indicators:

$$EIP_S = \{I_j \in \mathcal{J} | \mathcal{S}(I_j, s) = 1, \mathcal{A}(I_j) = 1, \mathcal{M}(I_j) = 1, \mathcal{F}(I_j) = 1\} \quad (3)$$

where S represents sensitivity to intervention (ToC-link), A spatial attribution to AoI, M market-mediated relevance, and F ex-ante feasibility (Primary/Proxy and data-effort).

2.3.3 Proxy Scenario-Driven and Value Functions

For each selected indicator *Ij*, the method defines a proxy dependent on the scenario drivers (e.g. potential users, opening hours including evening slots, intensity of events/activities, equivalent employees, generation of movements). To transform heterogeneous proxies into comparable values, each indicator is mapped to a score using anchored value functions, favouring interpretative anchors (0; 0.5; 1) based on policy criteria or technical plausibility, instead of purely statistical normalizations that require large samples. For cost indicators (e.g. mobility externalities), the value function is decreasing.

2.3.4 Aggregation, Compensability Policy, and Robustness

The EIP for a given scenario S_i is calculated as a weighted aggregation of indicator scores across intervention categories (K). The model combines two levels of weighting: category weights w_k and indicator weights v_{jk}. For each scenario, the performance of a given indicator j is transformed into a normalized value-function score $u_j(S_i)$. Considering J_k as the number of indicators in each category k:

$$EIP(S_i) = \sum = 1^k \; w \left(\sum = 1^J \; v \cdot u(S_i) \right) \quad (4)$$

Indicators are first aggregated within each category using the local weights v_{jk}, and the resulting category scores are combined using the global weights w_k. This aggregation ensures that the relative importance of categories and the contribution of individual indicators are considered [15]. The resulting EIP(S_i) provides a measure of the intervention potential of a given scenario S_i, allowing comparison among alternative strategies. Future applications may also incorporate sensitivity analyses to evaluate the stability of rankings under alternative weighting configurations

2.4 Preliminary Validation of the Proposed Framework

A preliminary validation of the proposed framework was carried out by checking its methodological consistency with previous ARP based applications. In particular, Module A builds on the Adaptive Reuse Potential model developed by Langston [4, 5] and on the ARPI model proposed by Anelli et al. [9]. The extension proposed in Module B was preliminarily validated through a conceptual consistency check with previous multicriteria and impact-oriented approaches to adaptive reuse assessment [6–8].

3 Conclusion and Future Directions

This paper proposes a methodological framework to support the assessment of the adaptive reuse potential of existing buildings, based on a structured and sustainability-oriented multicriteria approach. The methodological robustness of the framework is supported by the integration of validated ARP-based formulations structured indicator systems, and established multicriteria procedures widely adopted in adaptive reuse assessment literature.

Among the main strengths of the proposed framework is its continuity with previous ARP-based models and applications, which have demonstrated the feasibility of estimating adaptive reuse potential through physical life, useful life and obsolescence conditions [5, 6]. The framework is also consistent with studies that interpret adaptive reuse as a sustainability-oriented strategy capable of reducing demolition impacts, preserving existing building stock and supporting urban regeneration processes [15, 16, 18, 19]. In this perspective, the distinction between Module A and Module B allows the assessment to move from the intrinsic characteristics of the building to the potential impacts generated by reuse scenarios in the surrounding urban context. Although this preliminary validation does not replace a full empirical application, it supports the internal coherence and operational applicability of the framework. Future research will test the model on real case studies, including sensitivity analysis and comparison between compensatory and non-compensatory multicriteria techniques.

At the same time, the framework presents some limitations. AHP-based procedures remain sensitive to expert judgement, pairwise comparison consistency and weighting assumptions, thus requiring sensitivity and robustness analyses [20]. Moreover, the weighted additive aggregation adopted in the framework may generate compensatory effects among criteria. This issue is particularly relevant in sustainability-oriented assessments, where poor performance in one dimension should not always be offset by high performance in another [21]. Finally, the operational implementation of the framework depends on data availability and quality, especially when proxy indicators are used to estimate obsolescence or ex-ante urban impacts.

In conclusion, the proposed framework advances adaptive reuse assessment by expanding ARP-based methods from building-intrinsic reuse potential to ex-ante evaluation of territorial impacts of alternative reuse scenarios. Though needing full empirical validation, the framework is operational, grounded in established ARP/ARPI and multicriteria procedures, serving as a preliminary decision-support tool for public administrations and urban regeneration actors. Future case studies will enable calibration of indicators, testing of weighting assumptions, and comparison of aggregation methods.

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From Blade to Building: Structural Reuse of Wind Turbine Blades in Modular Envelope Systems

Thaleia-Pelagini Kalfa, Athanasios Svarnas(✉), M. Rafif Cahyadi Agung, Richard Nemcek, and Artemisia Goldsmith Ganzerli

Delft University of Technology, Mekelweg 5, 2628, CD Delft, Netherlands
svarnas.th@gmail.com

Abstract. This paper examines the architectural repurposing of decommissioned wind turbine blades (WTBs) as primary building envelope components through a design-led, material-driven research project. The study focuses on the segmentation of glass fiber–reinforced polymer (GFRP) blade components and their integration into modular wall and roof assemblies. WTB segments are treated as architectural elements, with geometry and material properties that directly affect the design.

The research is aided by the design and fabrication of a 1:1 physical mock-up to facilitate the testing of constructability, connection detailing, assembly sequencing, and the integration of non-standardized waste streams in the built environment. Through hands-on evaluation, the study demonstrates that blade segments can be cut, drilled, and mechanically connected without delamination, enabling blade-to-blade and blade-to-wood assemblies within modular wall and roof systems. At the same time, the research identifies critical constraints, including geometric variability between blades, transport and storage barriers, labor-intensive processing requirements, and the absence of established certification frameworks governing structural reuse of GFRP composite segments in building applications.

The findings highlight key enablers and barriers for scaling blade repurposing within architectural practice and inform future pathways for embedding decommissioned infrastructure materials into circular building systems. By characterizing WTBs as an urban mining resource instead of waste, this study shifts blade repurposing toward a transferable design framework for future circular construction applications, while outlining the technical, logistical and regulatory challenges that remain.

Keywords: Wind turbine blade · Repurposing · Circular construction · Design for disassembly · Urban mining · Material-driven design

1 Introduction

1.1 Problem Statement

Wind energy accounts for 29% of the Netherlands' electricity mix [1] and 18% across the European Union, with further expansion driven by EU renewable energy targets and long-term decarbonization strategies. While this transition reduces operational carbon

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emissions, it simultaneously generates a growing end-of-life (EoL) waste stream from wind turbine blades (WTBs) [2].

Unlike turbine towers and foundations, which are primarily steel and concrete and benefit from established recycling systems, WTBs consist largely of glass fiber–reinforced thermoset polymers (GFRP). These composites are irreversibly cured [3, 4], materially heterogeneous [5], and geometrically complex, making high-value recycling difficult. Consequently, landfilling and incineration – which rank lowest within the EU waste hierarchy – remain common disposal routes [6, 8]. Although landfill bans and industry commitments signal regulatory progress, they do not offer a solution to the increasing stock of decommissioned blades [9, 10].

While recycling technologies continue to develop, the systematic integration of WTB segments as primary structural components in building systems remains underexplored. In particular, segmentation logic, connection strategies, and envelope compatibility lack validation at an architectural scale.

This study investigates whether decommissioned WTB segments can function as structurally viable, mechanically connectable, and envelope-compatible components within modular building systems. Using a design-led experimental methodology combining digital modeling and full-scale prototyping, the research evaluates material processability, structural integration, and scalability.

1.2 The Waste Stream and End-of-Life Management

Current EoL pathways include landfilling, incineration with energy recovery, co-processing in cement kilns, recycling, and repurposing. Landfilling remains the simplest disposal strategy but performs poorly in environmental and resource-efficiency terms. Incineration and co-processing recover limited energy or mineral value but generate emissions and do not preserve structural integrity [3, 4].

Recycling strategies attempting to recover material value usually result in fiber degradation or require energy-intensive thermal or chemical processes. Mechanical grinding typically downcycles blades into filler materials with reduced structural performance [6]. Thermal and chemical processes can recover higher quality fibers, yet remain economically and energetically uncertain at scale.

Repurposing, by contrast, preserves structural integrity and extends service life. Structural reuse retains mechanical properties and embodied energy, enabling load-bearing applications and higher-value outputs [7, 12]. Existing precedents have demonstrated whole-blade reuse in infrastructure, playgrounds, and urban installations, however, these applications are often bespoke and limited in systemic scalability.

2 Methodology

This study adopts a design-led experimental methodology in which architectural prototyping functions as a research instrument to evaluate the structural reuse potential of decommissioned WTB segments.

The research unfolded in three phases. First, literature analysis established blade material composition, structural behavior, and EoL pathways. Second, geometrical mapping of a WTB and iterative development of a building design informed a segmentation

strategy aligned with architectural load paths. Third, a 1:1 prototype showcasing a key envelope detail was fabricated, to test assembly sequencing, cutting behavior, fastening performance, and resistance to delamination using standard tools.

A pragmatic approach was adopted in this study by focusing on a single blade typology. However, the principles that determine the design and the examined manufacturing techniques can be adapted across different blade types.

2.1 An Overview of Material Selection

In line with the project's circular design approach, the prototype building envelope was designed and built using almost exclusively reclaimed and recycled materials.

Wind Turbine Blades. WTBs are composite structures designed to maximize strength, stiffness, and durability while minimizing weight to ensure efficient energy generation and fatigue resistance. Although configurations vary between manufacturers, blades generally follow consistent material and geometric principles. They are characterized by a non-symmetrical, multi-cellular heterogeneous cross-section, split into the spar caps, edges, shell panels and shear webs, the material configurations of which are illustrated in Fig. 1. Approximately 80% of a blade's total mass consists of glass or carbon fiber reinforced polymer, composed of 60–70% structurally reinforcing fibers that are embedded in a thermoset polymer matrix which binds the structure and protects the fibers [3, 4, 5]. The Netherlands has 3,553 wind turbines [11], equal to 10,659 blades, representing a substantial and recurring local waste stream as turbines are decommissioned each year.

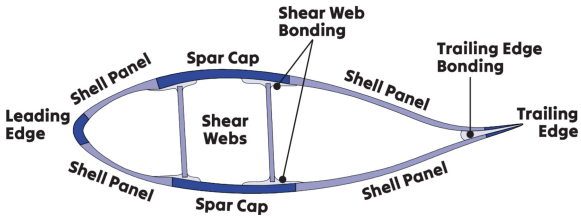


Fig. 1: Geometry and material composition of a WTB section showing: Spar Caps: Unidirectional (UD) glass/carbon fiber, supported by epoxy/UPR/VE/PUR matrix, Leading/Trailing Edge: Triaxial glass/carbon fiber, supported by structural adhesive, Shear Webs and Shell Panels: Triaxial GFRP sandwich laminates using balsa/PVC/PET matrix, Web and Edge Bonding: Epoxy/PUR-based structural adhesive, Surface Coating: PE/PUR-based lacquer

Other Secondary Materials. While the WTBs provide the main load-bearing structure, additional materials were required for framing, openings, connections, and insulation. Research and mapping of locally available resources confirmed availability for: reclaimed timber for framing, windows from specialized suppliers, steel bolts from demolition contractors for connections, and recycled materials for insulation. For this case study, the insulation is manufactured from recycled cotton textile waste.

3 Design

The design phase explored how WTB segments can inform an architectural system, translating their geometry and structural configuration into multiple building elements. All components are derived from a single blade, simplifying fabrication while enabling adaptable, repeatable designs.

A small-scale floating office demonstrator (Fig. 2) is developed as a speculative application in which blade segments define roof, walls, and platform components. Spatial organization and structural orientation are driven by blade curvature, thickness variation, and fiber distribution.

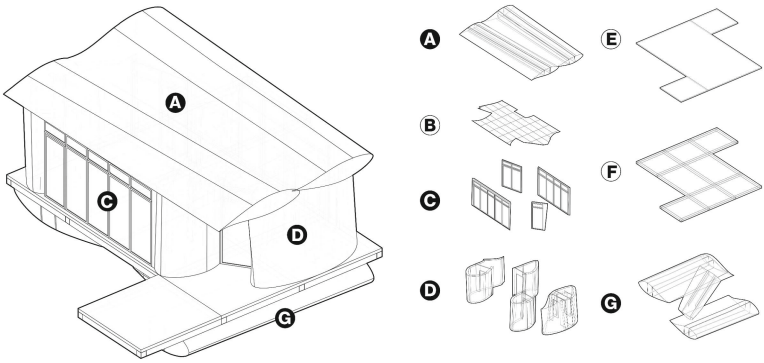


Fig. 2. Design overview for the proposed 'floating office', showing exploded elements with primary components made from WTB(*) labelled in black: Roof*, Ceiling panels, Timber fittings, Walls*, Floor System, Steel grid structural platform, Floating raft base*.

3.1 Building System and Blade Segmentation

The segment used for the mockup derived from a 30 m-long Fraunhofer-type WTB. However, for digital modeling, technical drawings of an NREL/5 MW/61.5 m WTB were used, as this WTB is one of the few with publicly available properties.

Segmentation follows the blade's internal structural logic. Spar caps, designed to resist high bending moments are reassigned as primary load-bearing zones within roof and wall elements. Their fiber continuity is maintained to preserve structural capacity. Shear webs inform internal stiffening strategies and contribute to local rigidity within assemblies. Shell panels and sandwich sections, characterized by lighter composite layups, are proposed as enclosure components where stiffness, durability, and surface continuity are required without high load demand. Through this approach, each blade region retains a role aligned with its original mechanical behavior, optimizing material utilization across the building system.

Blade segments form the exterior structural shell of roof and wall assemblies, functioning simultaneously as load-bearing structure and weather-resistant finish. To address waterproofing at exposed edges, a fiber-reinforced adhesive made from the same materials as the WTB is used to provide a robust seal and enable recyclability at the EoL.

This approach allows the project to ensure a high-performance barrier against moisture infiltration.

A lightweight timber substructure mediates between the curved composite surface and planar interior components, supporting insulation, vapor control layers, and reclaimed window interfaces. Openings are integrated through timber fittings that adapt to the blade's double curvature while allowing mechanical connection and disassembly. At the base of the proposal, blade segments are configured as buoyant elements within a floating platform system.

4 Manufacturing

4.1 Cutting, Assembly, and Connections

The 1:1 mock-up (Fig. 3) served as a functional validation of the proposed envelope system by focusing on the complex roof–wall–window interface to test structural integration, buildability, and reversibility alongside conventional construction logic. This full-scale prototype allowed for the simultaneous assessment of mechanical fastening and alignment at a critical convergence point, informing a production model that follows prefabrication strategy and on-site assembly.

The prototype starts with cutting the procured blade segment. A transverse cut that preserves the spar cap region to keep the structurally valuable portion intact and a longitudinal cut for a narrower segment suitable for vertical wall applications. This minimizes waste and maintains fiber continuity where possible.

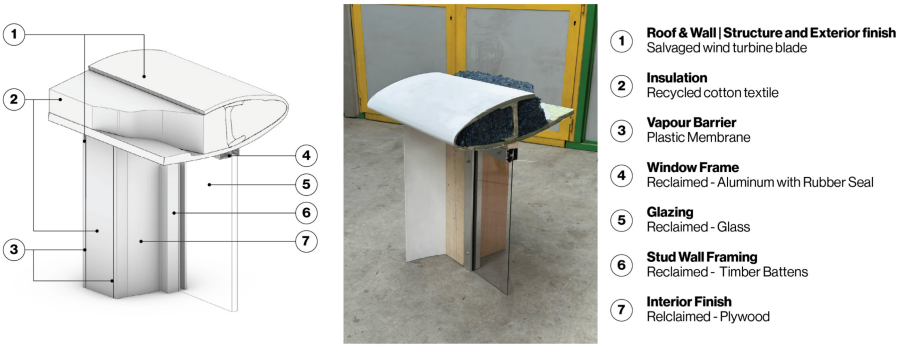


Fig. 3. Annotated schematic of mock-up detail illustrating build-up and structural layers, alongside image of final finished prototype.

The segments are then connected using a dowel joint technique with stud bolts. This enables vertical load transfer, rapid on-site alignment, and reduces the need for specialized tools. This also supports reversible construction principles since the connection can be disassembled without damaging the building elements.

Timber battens, acting as an interface between the WTB's curved surface and the window frame, were precision-cut to match the blade's geometry and fixed with stud

bolts. This connection was enabled through geometric mapping of the selected WTB segment and its transfer into a computational tool that was designed to generate the exact batten profile required – allowing for rapid adaptation to varying curvatures and rotations of different blade segments, supporting design flexibility.

The wall build-up consists of interior finish panels, a service cavity, reclaimed timber framing, insulation, vapor barrier membrane, and the blade shell acting simultaneously as structure and exterior finish. The window frame is then installed into the opening using mechanical fasteners into the timber battens.

4.2 Scalable Manufacturing and Design Framework

Scalability is supported by the concept's processing simplicity and potential for large-scale deployment, whereby WTBs can be rapidly segmented and directly repurposed as building elements enabling high throughput. The blade-to-building design approach is also adaptable across multiple small-scale building typologies beyond offices. Finally, feasibility assessment of the prototype's results suggests a pathway toward a scalable manufacturing framework which the authors envision as a 'Design and Build' practice. This would entail holistic project coordination, a proprietary material-informed parametric design software and a centralized robotic fabrication and processing facility. Specialized tasks such as blade decommissioning, pre-processing and transport would remain subcontracted.

5 Discussion and Conclusions

5.1 Discussion

The successful execution of this project identifies material affordances that challenge assumptions regarding the inaccessibility and technical complexity of WTB repurposing. Their structural reuse demonstrated robustness and adaptability within a materially informed design approach.

At the material scale, blade segmentation was achieved using standard hand tools, demonstrating that specialized equipment is not essential for primary processing. The composite accommodates drilling and mechanical fastening without significant splintering or delamination, enabling blade-to-blade assemblies through overlaps and custom joints. The inherent curvature, initially perceived as a design constraint, proved structurally and formally advantageous when strategically deployed, including its use for load-bearing purposes. The geometric variability also highlighted the need for localized adjustments and parametric tools. Crucial enabler to the design development and execution of construction details was the implementation of a computational design workstream, as demonstrated for the blade-to-building segmentation strategy and the custom timber connection between the curved composite blade and the planar framing and openings.

Despite successful prototyping, constraints to broader implementation remain. Repurposing WTBs at scale introduces significant handling and structural challenges due to aggregated weight and geometry, necessitating specialized transport, storage, and

processing facilities. Material and geometric variability across blade models complicates standardization; however, the proposed workflow achieves an adaptable approach accounting for various typologies. Finally, the absence of established certification frameworks for reused GFRP components places this material outside existing building codes, restricting structural application without rigorous engineering validation.

5.2 Conclusions

Positioning WTBs as an urban mining resource reframes blade waste as a construction opportunity. This project demonstrates that decommissioned blades can support circular building practices through prefabrication, computational adaptation, and design-for-disassembly. By linking infrastructure decommissioning with architectural production, the research contributes to circular construction models that prioritize high-value reuse and extend material lifecycles.

Future research should address structural testing, long-term durability, and fire performance – particularly critical for GFRP composites – as well as comparative life cycle assessment to quantify environmental benefits relative to recycling pathways. In addition, the development of digital inventory systems, parametric design tools, certification pathways, and standardized testing protocols will be necessary to enable integration into regulated construction markets.

Overall, this study provides insight into the technical challenges and opportunities associated with structural WTB reuse and demonstrates a manufacturing practice that advances blade repurposing beyond a niche design experiment. The findings suggest that further research is warranted to determine whether this might be a transferable circular strategy for incorporating large-scale composite waste streams into regenerative building systems.

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Integrating Geospatial and Earth Observation Technologies to Assess Urban Sustainability: A Systematic Literature Review

Katherine Athié[1](✉), Bruno Rocha[1], Luís Bragança[2], and Cristina Alvarez[1]

[1] Federal University of Espírito Santo, Vitória, Espírito Santo, Brazil
katherineathie@gmail.com
[2] University of Minho, Braga, Portugal

Abstract. Research on urban sustainability and urban morphology has traditionally focused on anthropogenic attributes of urban form, while giving less attention to natural systems and the health of urban ecosystems. Recent studies indicate that landscape connectivity, biodiversity, vegetation cover dynamics, and the relationships between urban form and natural systems remain underexplored, particularly in integrated and long-term spatial analyses. In response to this gap, this article conducts a systematic literature review on Earth Observation technologies applied to urban sustainability, emphasizing the integration of Remote Sensing (RS), Geographic Information Systems (GIS), and geospatial analyses to understand urban transformations and environmental impacts. The theoretical framework draws on contributions from sustainable urban morphology, landscape ecology, and geomatics, integrating recent reviews and empirical studies based on Earth Observation data. Methodologically, the review includes studies using orbital and geospatial data to analyze land use and land cover, urban expansion, built density, vegetation cover, and climate-related risks. The results indicate that these approaches enable the identification of consistent patterns of urbanization, vegetation loss, and urban thermal intensification, with implications for urban sustainability, ecosystem services, and land-use management. As its main contribution, the article systematizes climate-oriented analytical approaches, highlighting the potential of geospatial technologies to connect urban morphology and natural systems while supporting evidence-based territorial management strategies

Keywords: Urban Sustainability · Remote Sensing · Geomatics · Climate Change · Urban Ecosystems

1 Introduction

Urbanization has intensified significantly in recent decades, transforming landscapes and generating complex environmental challenges for cities. Projections indicate that 68% of the global population will live in urban areas by 2050 (Wellmann et al., 2020), increasing pressure on natural systems and contributing to environmental degradation, biodiversity loss, and the intensification of climate-related risks. Although studies on sustainable

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urban morphology have advanced in recent years, recent reviews highlight limitations related to the limited incorporation of indicators of natural systems and ecosystem health into analyses of urban form (Zhang et al., 2023).

Cities can be understood as Socio-Ecological-Technological Systems, in which the spatial configuration of built and natural elements influences environmental performance and the provision of ecosystem services (Wellmann et al., 2020). The increasing availability of satellite image time series and geospatial products has expanded the capacity to monitor these transformations, supporting more integrated and consistent urban environmental analyses (Wulder et al., 2019).

Satellite imagery enables the monitoring of land use and land cover changes, vegetation distribution, and urban thermal patterns, allowing the quantification of indicators such as Land Surface Temperature (LST), vegetation indices (NDVI), and Land Use/Land Cover (LULC) patterns. Recent studies have demonstrated that these approaches contribute to analyses related to outdoor thermal comfort and urban environmental performance (Manapragada et al., 2025).

Studies demonstrate the relevance of these approaches for understanding the relationships between urbanization and environmental change. Dessu et al. (2020) found that urban expansion associated with vegetation loss influenced local climatic conditions, and Qin et al. (2025) demonstrated that blue and green spaces contribute to regulating land surface temperature and improving urban microclimates. Other studies highlight the potential of Nature-Based Solutions (NBS) and ecosystem-based strategies for thermal mitigation and improving urban environmental performance (Santos et al., 2021; Zuo et al., 2022; Toscan et al., 2025).

Despite the growing number of empirical studies applying RS to urban environmental analysis, the literature remains fragmented across different thematic domains, often addressing urban climate, vegetation monitoring, and land use change separately. This study conducts a systematic literature review on the application of EO technologies, particularly RS and geomatics, to urban sustainability analysis under climate change conditions. The review aims to identify how these technologies have been employed to assess urban sustainability and to systematize recurring methodological trends and analytical approaches by organizing the literature around three dimensions: urban climate dynamics, urban vegetation and green infrastructure, and LULC changes associated with urban expansion. By integrating these dimensions, this study seeks to strengthen ecosystem-based and spatial approaches applied to sustainability-oriented urban planning, supporting more efficient and resilient territorial strategies.

2 Methodology

This study adopts a Systematic Literature Review (SLR) to identify and analyze recent scientific contributions on the application of Earth observation (EO) technologies, especially RS, to urban sustainability assessment. The review followed principles of transparency, traceability, and reproducibility widely adopted in systematic reviews, including the PRISMA protocol.

The bibliographic search was conducted in the Scopus and ScienceDirect databases, selected due to their broad coverage of journals in the fields of urban studies, environmental sustainability, geospatial technologies, and EO applications. The search strategy

was structured around three thematic axes — urban sustainability, EO technologies, and climate change — using the following Boolean search string: ("urban sustainability" OR "sustainable urban development") AND ("remote sensing" OR "satellite imagery" OR "Earth observation" OR "geospatial technologies") AND ("climate change" OR "climate crisis"). The search considered the occurrence of these terms in titles, abstracts, and keywords.

Peer-reviewed articles published between 2020 and 2025 were included if they explicitly addressed the application of RS, satellite imagery, or geospatial technologies in studies related to urban sustainability, urban planning, or environmental assessment in urban areas. Duplicate studies, research unrelated to urban contexts, studies in which RS appeared only marginally, and non-peer-reviewed publications were excluded. In the full-text review stage, studies lacking adherence to the proposed analytical dimensions or without a direct relationship between geospatial technologies and urban sustainability were also excluded.

The initial search identified 118 records (93 from Scopus and 25 from ScienceDirect). After removing 21 duplicates, 97 studies remained for screening. Title and abstract analysis resulted in the preliminary selection of 59 articles, which were subsequently evaluated through full-text review. After thematic refinement, the final sample comprised 42 scientific articles.

The selected studies were organized into an analytical matrix containing authors, year of publication, journal, research focus, type of RS data, and environmental indicators employed, including NDVI, LST, NDBI, and LULC dynamics. A thematic analysis was then conducted to identify recurring methodological trends and analytical approaches. Based on this analysis, the studies were grouped into three thematic categories: urban climate and urban heat islands (18 articles), urban vegetation and green infrastructure (13 articles), and land use changes associated with urban expansion (11 articles).

3 Results and Discussion

3.1 Overview of the Literature and Methodological Approaches

The reviewed studies demonstrate the growing use of RS and satellite data from open-access platforms, especially the Landsat and Sentinel missions, in the investigation of urban environmental processes. These approaches enable the monitoring of urban landscape transformations and support analyses related to climate dynamics, vegetation distribution, and land use change. According to Wulder et al. (2019), the integration between Landsat — an Earth observation program in continuous operation since 1972 — and Sentinel-2 expands the spatial and temporal coverage of data, strengthening multitemporal analyses.

Recent literature highlights the predominance of multispectral imagery associated with indicators such as Land Surface Temperature (LST), vegetation indices (NDVI and EVI), and Land Use and Land Cover (LULC) classifications. Studies also emphasize the growing integration between RS, GIS, LiDAR data, and ML techniques, reflecting a methodological trend toward integrated analyses of urban morphology and urban ecological processes. According to Manapragada et al. (2025), these approaches expand the

capacity to analyze urban thermal dynamics, outdoor thermal comfort, building energy consumption, and solar potential.

In addition to orbital imagery, several studies incorporate complementary geospatial datasets, including OpenStreetMap, the Human Settlement Layer, and cloud-based geospatial platforms, expanding the capacity to represent built density, urban configuration, and interactions between vegetation, and urban microclimates. These techniques support long-term analyses of territorial transformations and their environmental impacts. Dessu et al. (2020) demonstrated how urban expansion associated with vegetation loss contributed to local climatic changes in urban centers of southwestern Ethiopia. Similarly, Ruiz-Valero et al. (2026) integrated satellite imagery, LiDAR data, and Bayesian hierarchical models to analyze the cooling capacity of urban tree canopy cover in Málaga, Spain.

Overall, the reviewed studies indicate a growing integration between thermal metrics, vegetation indicators, and land use analyses, reinforcing the understanding that urban climate, green infrastructure, and urban expansion constitute interdependent dimensions of urban sustainability. Table 1 summarizes the main approaches, indicators, and applications identified in the reviewed literature. Nevertheless, limitations related to the spatial and temporal resolution of sensors, classification uncertainties, interoperability between platforms, and unequal data availability persist. These limitations hinder comparisons between studies and restrict the operational application of part of the environmental indicators derived from RS.

Table 1. Summary of the main RS approaches applied to urban sustainability

Dimension	Technologies	Indicators	Applications
Urban climate	Landsat, Sentinel-2, GIS	LST, NDVI NDBI	Thermal dynamics
Green infrastructure	Landsat, GIS	NDVI, LST	NBS
Urban expansion	Landsat, GEE	LULC, LST	Soil sealing

3.2 Urban Climate and Urban Heat Islands

A substantial portion of the reviewed literature investigates urban climate dynamics, particularly the relationships between UHI, urban morphology, and land cover transformation. These studies predominantly employ satellite-derived indicators such as Land Surface Temperature (LST), often combined with vegetation and imperviousness indices such as NDVI and NDBI.

Halder et al. (2021) investigated the impacts of climate change on urban heat islands using satellite-derived geospatial indicators. More recent studies expanded these analyses through thermal vulnerability and spatial modeling approaches. Pradeep Kumar et al. (2023) analyzed thermal comfort zones in semi-arid regions, while Li et al. (2024) integrated RS and ML to assess urban heat vulnerability.

Other studies examine the evolution of urban heat islands in rapidly urbanizing contexts. An et al. (2025) demonstrated that urban expansion and land cover transformations directly influence urban thermal patterns in Harbin, China. Similarly, Hasyim et al.

(2025) identified relationships between population density, land use, and increasing land surface temperature, highlighting the role of intensive urbanization in the intensification of urban heat islands.

Overall, the reviewed studies indicate a strong association between urban expansion, increasing impervious surfaces, and the intensification of urban heat islands, while vegetated areas and Nature-Based Solutions (NBS) present recurring mitigating effects. These findings reinforce the importance of incorporating thermal and vegetation-cover indicators into urban planning strategies aimed at climate adaptation and improving urban environmental quality.

3.3 Urban Vegetation and Green Infrastructure

Another group of studies examines the role of urban vegetation and green infrastructure in mitigating climate impacts and strengthening urban ecosystem services. These studies mainly employ satellite-derived vegetation indices to assess vegetation cover, cooling capacity, and the distribution of green infrastructure in cities.

Santos et al. (2021) used RS and GIS to model the potential of green roofs at different scales, highlighting their relevance for urban sustainability strategies. Kamal (2023) applied automated image extraction techniques from satellite imagery to estimate vegetation loss and support climate adaptation strategies. Other studies focused on the cooling effects associated with vegetation and Nature-Based Solutions (NBS). Zuo et al. (2022) quantified the thermal performance of green roofs under different urban configurations, while Shi et al. (2023) analyzed the relationship between urban parks and thermal comfort in industrial cities.

Recent research also demonstrates growing interest in the interactions between vegetation, water bodies, and urban microclimates. Qin et al. (2025) identified synergistic cooling effects associated with the integration of blue and green spaces in Fuzhou, China, demonstrating that spatial configuration and ecological complexity influence land surface temperature patterns. Similarly, Toscan et al. (2025) analyzed the impacts of NBS on land cover dynamics and urban temperatures in Guimarães-Portugal using multitemporal Landsat imagery and ML. Ruiz-Valero et al. (2026) also demonstrated the cooling capacity of urban tree canopy cover through the integration of satellite imagery and spatial modeling.

The reviewed studies indicate a growing trend toward the use of NBS and green infrastructure as spatially efficient strategies for thermal mitigation, climate adaptation, and strengthening urban resilience. In addition to microclimatic benefits, these approaches contribute to the preservation of ecosystem services and the more efficient use of urban land, reinforcing their relevance for sustainability-oriented urban policies.

3.4 Land Use Change and Urban Expansion

A third thematic group focuses on urban expansion and land use and land cover changes, investigating how territorial transformations influence urban environmental conditions. RS has played a central role in monitoring these dynamics, enabling the identification of patterns associated with urban growth, soil sealing, and vegetation loss.

Criado et al. (2020) conducted a multitemporal analysis of soil sealing and land use change in Salamanca, Spain, using Landsat imagery and historical aerial photographs between 1956 and 2018. The authors identified significant urban expansion over agricultural and environmentally sensitive areas. Dessu et al. (2020) documented similar trends in Ethiopian urban centers, demonstrating that accelerated urban growth was accompanied by reductions in vegetation and agricultural land.

More recent studies incorporate cloud-based geospatial platforms and ML techniques to expand the scale and accuracy of urban spatial analyses. Biswas et al. (2023) used Google Earth Engine and ML algorithms to map land use changes in Chattogram, Bangladesh, demonstrating the potential of these platforms for large-scale urban monitoring. Sonet et al. (2025) analyzed urban expansion patterns and thermal characteristics in rapidly growing megacities, highlighting relationships between intensive urbanization, land cover transformation, and increasing land surface temperature.

Overall, the analyzed studies demonstrate that LULC dynamics, vegetation loss, and urban thermal intensification constitute interdependent processes associated with accelerated urban expansion. These findings reinforce the importance of continuous spatial monitoring to support strategies aimed at more efficient land use, environmental impact mitigation, and preservation of urban ecological infrastructure.

The reviewed studies also indicate that the integration between RS, spatial modeling, and geospatial datasets expands the capacity to analyze relationships between urban morphology, ecological processes, and urban sustainability. Despite methodological advances, challenges related to the integration between RS, urban ecology, and territorial planning persist, as well as the translation of geospatial indicators into tools applicable to urban management. In this context, the results highlight the need for more integrated and operational approaches to sustainability-oriented urban planning, climate adaptation, and efficient land use.

4 Conclusion

The results highlight that EO technologies, especially RS and geomatics, enable the monitoring of land use and land cover change, vegetation distribution, and urban thermal dynamics, contributing to integrated analyses of urban morphology and ecological processes. The growing integration between RS, GIS, LiDAR data, and spatial modeling expands the capacity to represent interactions between the built environment, green infrastructure, and urban environmental conditions. The studies also demonstrate that urban climate, vegetation, and land use and land cover change constitute interdependent dimensions of urban sustainability, frequently associated with urban expansion, soil sealing, and thermal intensification.

Despite methodological advances, the literature remains fragmented across different thematic domains and still presents limitations related to the integration between RS, urban ecology, and territorial planning. Challenges associated with sensor resolution, interoperability between platforms, unequal data availability, and the institutional and operational complexity of EO systems—especially in contexts of the Global South—also persist. The reviewed studies highlight the relevance of Nature-Based Solutions (NBS) and green infrastructure for thermal mitigation and climate adaptation. In this

context, the results reinforce the potential of geospatial technologies to support evidence-based territorial strategies for efficient land use and ecosystem service preservation. Finally, future research may advance in the development of more integrated approaches capable of articulating EO data, urban morphology indicators, and ecosystem metrics into frameworks more applicable to sustainability-oriented urban planning.

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Review of Sustainable Construction Ecosystem in Kosovo

Ajtene Avdullahi[1](✉), Besart Hajrizi[1], Qazim Tmava[1], Arif Krasniqi[1], Vjosa Fejza Ademi[2], Brikene Dionizi[3], and Ermira H. Kalaj[3]

[1] University "Isa Boletini" in Mitrovica, Mitrovica, Kosovo
[2] University of Prishtina, Prishtina, Kosovo
[3] University of Shkodra "Luigj Gurakuqi", Shkodër, Albania
ajtene.avdullahi@umib.net

Abstract.
Purpose The construction market in Kosovo is still dominated by linear traditional construction practices, which are not sufficiently environmentally friendly. Recently, urgent needs for sustainability, resilience and circularity have emerged, challenging these conventional methods. This study aims to analyze the emerging ecosystem of sustainable construction in Kosovo by examining industry initiatives, private sector competitors, and stakeholder collaborations that drive systemic change

Methodology This research employs a desk research-based approach combined with qualitative descriptive analysis. To gain primary insights, in-depth interviews were conducted with the founder/director of the Kosovo Green Building Council (KGBC). This methodology allows to evaluate how stakeholders coordinate and apply sustainable strategies within the local ecosystem

Findings and Discussion The paper identifies key actors within the ecosystem, such as the Kosovo Green Building Council (KGBC), a non-governmental organization dedicated to advancing green standards and professional development. KGBC aims to serve as a bridge connecting stakeholders from the public and private sectors. In the private sector, businesses like InstaBuilt illustrate the advanced techniques that are changing the construction industry. InstaBuilt is one of the largest construction factories in Southeast Europe, creating environmentally friendly, wood-based modular housing systems that reduce embodied carbon and improve resource efficiency

Conclusion The research concludes by assessing the level of coordination among stakeholders and the effectiveness of current techniques and strategies in fostering a sustainable ecosystem. By highlighting the synergy between NGO advocacy and private sector innovation, the paper underscores the necessary transition from traditional to circular construction practices in Kosovo

Keywords: Sustainable Construction · Stakeholder Collaboration · Green Building Ecosystems · Circularity · Kosovo

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1 The Overview of Construction Sector in Kosovo

The industry of construction remains a cornerstone of Kosovo's economy, showing consistent growth during 2025 in tax contributions and business registrations. Based on data from the Kosovo Agency of Statistics, the GDP contribution from the construction sector reached €242.54 million in the third quarter of 2025 [1]. According to data from the Kosovo Business Registration Agency, there are approximately 12,684 construction businesses registered during 2025 [2]. However, based on data from the Tax Administration of Kosovo, only 4,258 construction companies are currently active tax declarants [3]. This indicates that a significant number of registered businesses are either not economically active or fail to declare and pay taxes regularly.

As reported in the annual report of the Tax Administration of Kosovo for 2025, the construction industry has been identified as a high-priority area for revenue collection and formalization [3]. Total tax revenues for the period January–August 2025 reached €713.3 million, an increase of €71.2 million (10.6%) compared to the same period in 2024 [3]. Hence, stricter reverse charge VAT applications have been enforced for construction services to prevent tax evasion [3].

2 Methodology

This study adopts a mixed-method approach, combining qualitative descriptive analysis with quantitative desk research to provide a comprehensive overview of the sustainable construction ecosystem in Kosovo. The study evaluates both the maturity of the sustainability transition in this sector and its economic scale.

The first part of the research is based on official reports and statistical databases published in 2025. Key sources include TAK, KBRA, KAS, and reports from international organizations such as EBRD, UNDP, and GIZ [1–3, 13–16]. To capture the green transition, the study conducted a semi-structured in-depth interview with a key pioneer actor within the local ecosystem, namely the founder and director of the Kosovo Green Building Council (KGBC). The selection was based on KGBC's central role in advocacy and private sector innovation.

The qualitative data was processed using thematic coding to categorize industry barriers and drivers. A cross-referencing method was applied to compare qualitative findings with quantitative data from TAK and KAS [1, 3]. This approach enabled identification of implementation and compliance gaps between sustainable certification practices and economic output.

3 Emerging Ecosystem of Sustainable Construction in Kosovo

Based on international funding support and private innovation, 2025 has seen a gradual shift toward green construction standards, although traditional practices still dominate in Kosovo [13, 14]. Kosovo's ecosystem for sustainable construction remains in an early stage of development [4]. Its key features include increasing awareness of environmental

regulations, energy efficiency, and sustainable building practices. Due to insufficient promotion, citizens remain relatively uninformed about the benefits of sustainable construction [4]. Sustainable construction offers economic, social, and environmental benefits such as energy savings, reduced operational costs, lower CO_2 emissions, and improved occupant well-being [4]. Utilizing resources more effectively is necessary to transition to a sustainable economy [5]. However, challenges remain largely organizational, structural, economic, and regulatory [4].

There are several interrelated actors in Kosovo's emerging ecosystem of sustainable construction (see Fig. 1). All of these actors work together to create a growing environment that facilitates the shift to sustainable building. The regulatory and policy framework for sustainable construction is mostly shaped by public institutions.



Fig. 1 Emerging Ecosystem of Sustainable Construction in Kosovo

3.1 Government and Public Institutions

Sustainable building practices are implemented by developers and construction businesses, while government institutions offer the policy direction and regulatory framework. A combination of institutional obligations and evolving legal instruments create Kosovo's regulatory environment for sustainable construction. The regulatory framework is shaped by public institutions that provide policy direction and legal instruments. Key institutions include the Ministry of Environment, Spatial Planning and Infrastructure [6] and the Ministry of Economy [7]. The framework is defined by the Law on Construction [8], the Law on Energy Efficiency [9], and the Law on Energy Performance of Buildings [10]. Additional support is provided by the Renewable Energy Law [11] and financial mecha-nisms such as the Kosovo Energy Efficiency Fund [12].

3.2 Universities and Research

Higher education institutions contribute through programs in civil engineering and architecture. The University of Prishtina and the University for Business and Technology integrate sustainability concepts such as energy efficiency and green construction into their curricula [4].

3.3 International Organizations

The construction sector started to progressively embrace green building concepts including better insulation, the integration of renewable energy, and resource-efficient materials thanks to donor-sponsored programs and compliance with EU standards. International actors play a key role in advancing sustainable construction. Helvetas promotes green materials and technologies through the RECONOMY program [13]. Establishing Green Building Councils is one strategy that promotes industry-wide standards and gives women and youth access to green jobs [13]. The World Bank and EBRD finance large-scale energy efficiency projects in public buildings [14, 15]. The European Union supports infrastructure and sustainability initiatives through programs such as the Western Balkans Investment Framework [16]. UNDP contributes through advisory support and capacity-building activities [17].

3.4 Private Sector

Private sector innovation is emerging but remains limited. InstaBuilt represents an advanced example of green construction, focusing on modular housing and embodied carbon reduction [18]. Similarly, the Innovation and Training Park (ITP) in Prizren has developed energy-efficient infrastructure and renewable energy capacity [19].

3.5 Financial Institutions

Financial institutions, particularly commercial banks, are increasingly supporting sustainable construction through green financing mechanisms. Some banks have introduced loan products that support energy-efficient construction and renovation, often in collaboration with international financial institutions [15].

3.6 NGOs

NGOs such as Balkan Green Foundation contribute through research, advocacy, and public engagement on environmental and climate-related issues [20]. These organizations often collaborate with international partners and institutions to support the development of standards, training, and awareness campaigns [20].

3.7 Industry Associations

The Kosovo Green Building Council (KGBC) is a non-governmental, non-profit organization that operates as a professional association promoting sustainable construction practices. It plays a key role in promoting sustainable construction practices and bridging the gap between policy and private sector engagement [21]. KGBC serves as the primary NGO advocate, facilitating the "Green Business & Industry Summit" and the "Green Business Expo 2025" in Pristina to bridge the gap between public policy and private green investment [22].

4 Analysis and Discussion

According to the data gathered in this study and presented in the Table 1, we can conclude that the transition toward a sustainable construction ecosystem in Kosovo is characterized by a significant gap between officially registered businesses and those actively participating in the market. The construction industry remains a primary economic driver, the qualitative data gathered from the Kosovo Green Building Council (KGBC) emphasizes that the market for sustainable building is still in its initial stage of maturity. The following analysis examines the systemic obstacles and barriers, and strategic drivers identified by key stakeholders.

According to the data gathered from the interview with the Founder and Director of KGBC to shift toward green building, the most important incentives and forces are: rising energy costs and EU standards. Hence, based on this suggestion, internal policy incentives are weaker in supporting and driving sustainability in Kosovo than immediate economic necessity and external regulatory pressure (EU Standards). On the other hand, the lack of government incentives and high initial capital costs remain the strongest barriers to widespread adoption. This financial barrier is accompanied by a technical skill gap in the local workforce, which has a direct impact on limiting the capacity of construction firms to implement complex green technologies.

Nevertheless, the construction industry is recognizing the necessity future of the green standards but is still hindered by short-term fiscal constraints. During the interview, the director of KGBC, emphasized that the private sector engagement is low, and on the other hand the long-term economic value is perceived as positive. "*We established KGBC to bridge the gap between outdated construction norms and the urgent need for energy-efficient urban development*" (K-01).

Table 1. Summary of semi-structured in-depth interview

Interview ID	**K-01**
Respondent Role	Founder & Director
Core Mission & Gap	Advocating for sustainable standards; filling the gap in energy efficiency regulations and green building certification.
Market Maturity (Early/Dev/Adv)	Early Stage
Main Drivers (1=EU Standards, 2=Energy Costs, 3=CSR, 4=Policy)	1, 2
Main Barriers	High initial capital costs, lack of government incentives, and limited technical expertise in the local workforce.
Notable Projects/ Initiatives	Green Building Weeks, Policy Advocacy, Certification Training
Private Sector Engagement (High/Med/Low)	Low
Perceived Economic Value (Pos/Neut/Neg)	Positive (Long-term)
Primary Stakeholder Partner	Government (Ministry of Environment) & International NGOs
Future Outlook (5-10 yrs)	Shift toward mandatory energy performance certificates and LEED/BREEAM alignment.
Key Quote	"We established KGBC to bridge the gap between outdated construction norms and the urgent need for energy-efficient urban development."

5 Conclusion

According to the data related to the Tax Administration of Kosovo [3], only 4,258 are active tax declarants, while there are 12,684 registered construction businesses. A critical compliance gap is reflected by the data, that extends from environmental standards to tax declarations. Meanwhile, the mission of KGBC is supported by international partners and not too much supported by any state legislative framework. However, the future of

this industry for the next 5–10 years remains optimistic, with a projected shift toward mandatory energy performance certificates. To achieve this, the cooperation between advocacy groups like KGBC and private sector innovators like InstaBuilt and other stakeholders, will be essential in moving Kosovo toward a circular economy.

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Adaptive Natural Ventilation Strategies in Scotland's Office Building: Impact on Indoor Air Quality and Comfort

Ariakpoze Jessica Eyaefe(✉), Mina Jowkar, and Nirodha Fernando

Edinburgh Napier University, Edinburgh EH10 5DT, UK
40683718@live.napier.ac.uk

Abstract. This study assesses the effectiveness of adaptive natural ventilation (ANV) strategies in improving indoor air quality (IAQ) and thermal comfort in a Scottish university office building. A mixed-methods approach was used, including simultaneous environmental monitoring and occupant surveying. Results show that although the ambient environmental conditions generally aligned with adaptive comfort guidance in ASHRAE 55 (2023) and EN 16798–1:2019, low indoor air quality and thermal dissatisfaction were reported due to restricted airflow, inaccessible windows, and inconsistent operation during colder periods. Key barriers including spatial design limitations, limited user interaction, and climatic variability are also discussed. The findings highlight the importance of user-responsive ventilation systems that incorporate automated controls and adaptive design to enhance energy efficiency, occupant well-being, and climate resilience in office buildings

Keywords: adaptive natural ventilation · indoor air quality · thermal comfort · sustainable buildings · occupant perception · office environments

1 Introduction

The building sector contributes around 39% of global energy-related CO_2 emissions, with ventilation systems accounting for a significant share of operational energy use in non-residential buildings [1, 2]. In the UK, higher education buildings consume approximately 5.2 billion kWh of energy annually [3], highlighting the importance of improving indoor environmental strategies to reduce energy demand and associated greenhouse gas emissions. However, energy efficiency measures must ensure that occupant thermal comfort and indoor air quality are not compromised. In response to these energy saving strategies, Natural Ventilation (NV) is widely promoted as a low-energy strategy that can reduce reliance on mechanical systems while maintaining indoor air quality (IAQ) and thermal comfort through passive airflow [2, 4]. However, its effectiveness is highly climate dependent. In cold and variable climates such as Scotland, low temperatures, humidity, and fluctuating wind conditions can limit airflow and reduce ventilation efficiency [5, 6]. In addition, occupant reluctance to open windows during colder periods

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and physical constraints such as single-sided ventilation in deep office spaces can result in low air velocities, stagnant zones, and poor perceived air quality despite acceptable CO_2 levels [7, 8]. Adaptive natural ventilation (ANV) adjusts airflow pathways and window operation in response to environmental conditions and occupant interaction [9]. Although simulation studies show that NV and ANV can reduce energy demand while maintaining acceptable indoor conditions [10], empirical evidence of their real-world performance in cold-climate office buildings remains limited. In regions such as Scotland, a key challenge is balancing heat retention and fresh air exchange [11, 12]. Highly airtight buildings designed for energy efficiency can lead to the accumulation of CO_2, moisture, and VOCs, increasing the risk of poor indoor air quality and Sick Building Syndrome (SBS) [2]. This issue may be further intensified by occupants' reluctance to open windows during winter, creating an indoor air quality–energy paradox [7]. This research gap is particularly relevant in Scotland, where many office buildings are historic or retrofit-sensitive and therefore constrained in terms of ventilation design [7, 13]. Understanding the relationship between measured environmental conditions and occupants' perception is essential for adaptive comfort evaluation in naturally ventilated office buildings.

This study evaluates the effectiveness of adaptive natural ventilation (ANV) strategies in improving indoor air quality (IAQ) and thermal comfort in a university office building in Scotland. Using in-situ environmental monitoring and occupant surveys, the research examines IAQ, thermal conditions, and window-use behaviour. The measured performance was evaluated using adaptive thermal comfort guidance in ASHRAE 55 -2023 [14] and EN 16798-1:2019 [15] to identify potential gaps between regulatory compliance and occupant perception, providing in-sights for climate-responsive and user-centred ventilation design in cold-climate regions.

2 Methodology

This study used a mixed-methods approach, combining in-situ environmental monitoring and structured occupant surveys in a naturally ventilated university office in Scotland (Fig. 1). Ventilation was provided through six high-level, single-sided operable windows along one façade. The partitioned office layout and a closed rear door limited cross-ventilation potential.

2.1 Environmental Monitoring and Data Collection

Environmental monitoring was conducted over a two-week period (14–28 March 2025, excluding weekends) during working hours (09:00–17:00)

Parameters Measured includes Carbon dioxide (CO_2) concentration, Indoor air temperature, Relative humidity (RH), Air velocity, Particulate matter ($PM_{2.5}$ and PM_{10}). CO_2 was used as an indicator of ventilation effectiveness. Temperature and RH were used to assess thermal comfort conditions. Air velocity was measured to evaluate airflow performance. All monitoring devices were strategically placed at a height of 1.1 m centrally within the office to avoid direct sunlight, draughts, and equipment interference, ensuring representative indoor readings. The parameters and their respective monitoring devices are summarized in Table 1.

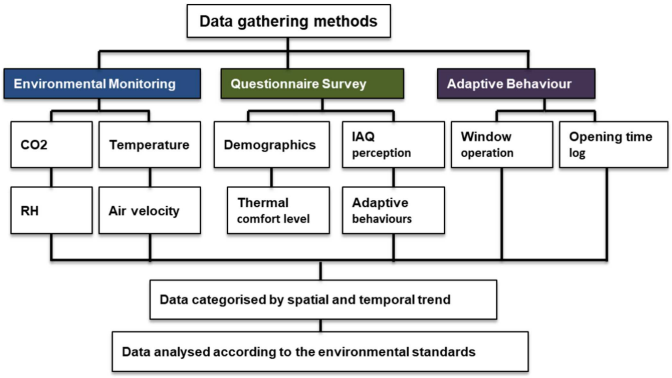


Fig. 1: overview of the data gathering methods

Table 1. Technical specifications of monitoring equipment

Measured Parameter	Instrument	Range	Accuracy
Air Temperature	INKBIRD IBS-TH3 PLUS	0–50 °C	±0.3 °C
Relative Humidity	INKBIRD IBS-TH3-PLUS	0–99 %RH	±3% RH
CO_2 Concentration	Qingping Air Monitor Lite	400–9999 ppm	±15%
PM2.5 / PM10	Qingping Air Monitor Lite	0–500 µg/m^3	Not specified
Air Velocity	Swema 03 Anemometer	0.05–3.00 m/s	±0.03 m/s

2.2 Questionnaire Survey (Table 2)

Table 2. Summary of participant

Office Type	Capacity	Group	Gender	Age Range	Mean Age	Activity Level
Shared research office	Designed for 24 occupants	Research students (N = 15)	8 Male and 7 Female	25–55 Years	32 Years	1.1–1.2met

3 Results

Carbon dioxide (CO_2) concentrations during the monitoring period ranged from 556 ppm to a peak of 1123 ppm, with an average value of 725 ppm. Mean concentration presented in Fig. 2a, remained below the commonly referenced 1000 ppm threshold for office environments [15, 16]. However, exceedance above 1000 ppm occurred during peak occupancy on 21 March 2025, indicating periods of insufficient ventilation. These fluctuations

indicate intermittent under-ventilation, particularly during afternoon occupancy peaks. Indoor temperature ranged from 18.4 °C to 26.6 °C (mean: 23.4 °C). These values fall within the acceptable adaptive comfort ranges recommended by ASHRAE 55 (2023) for naturally ventilated offices. Relative humidity ranged between 30.9% and 58.4% (mean: 41.4%), remaining within the recommended 30–60% indoor comfort range. Particulate matter concentrations ($PM_{2.5}$ and PM_{10}) remained between 0–3 μg/m^3, well below WHO guideline limits, showing minimal particulate-related air quality concerns during the monitoring period.

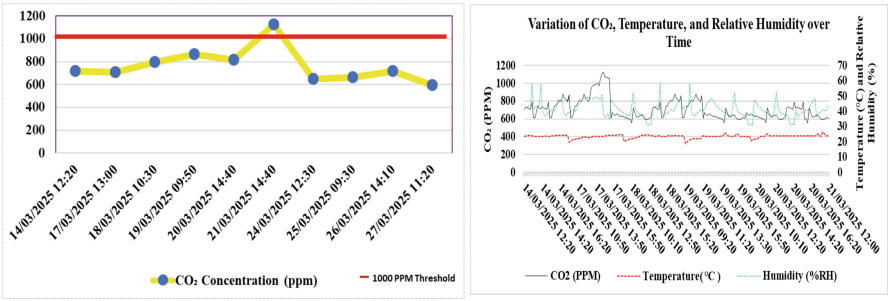


Fig. 2 **a**. CO2 concentration and **b**. IAQ Trend during monitoring period

In contrast to these compliant parameters, air velocity ranged from 0.013 to 0.051 m/s (mean: 0.048 m/s), substantially below the perceptible airflow threshold of 0.15–0.25 m/s recommended for naturally ventilated spaces (Fig. 3). This empirical value provides a scientific basis for the 73% dissatisfaction rate recorded in the surveys. While most environmental parameters complied with standards, extremely low air velocity indicates limited effective air movement within the space.

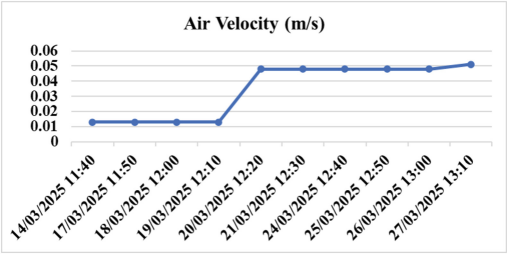


Fig. 3. Recorded air velocity during monitoring period

3.1 Occupant Comfort Perception

Following analysis of the environmental data, the occupant thermal comfort and perception of indoor air quality were analysed and the results provided in the following sections.

Thermal Comfort. Survey responses indicated that most occupants reported neutral to slightly warm sensations on the ASHRAE thermal sensation scale, with the mean TSV of 1.1. Despite measured temperatures falling within adaptive comfort ranges, several occupants reported discomfort associated with insufficient airflow and air movement which influenced perceived thermal conditions more strongly than temperature alone. To understand the relationship between these variables, a Pearson Correlation Matrix was utilized (Table 3).

Table 3. Pearson Correlation Matrix

	Temperature	Humidity	CO_2	Air Velocity
Temperature	1			
Humidity	−0.094	1		
CO_2 (PPM)	−0.089	0.239	1	
Air Velocity	−0.135	0.085	0.239	1

Perceived Indoor Air Quality. Forty percent (40%) of respondents reported experiencing "stuffy or stale air," while 13.3% reported dry air and 13.3% unpleasant odours. Although CO_2 levels were generally compliant, perceived air freshness did not fully align with measured concentrations. Reported symptoms included fatigue, headaches, and respiratory discomfort, consistent with mild SBS indicators (Fig. 4).

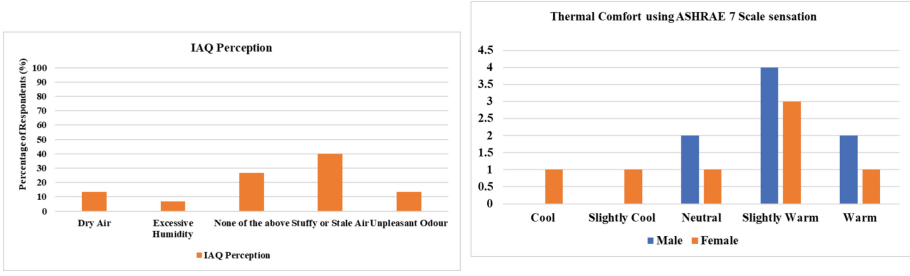


Fig.4 **a**. Perceived IAQ concerns, and **b**. TSVs reported by occupants

Window operation was inconsistent. 20% reported opening windows daily, 26.7% opened windows a few times per week, 33.3% occasionally, 20% rarely or never. Cold weather was identified as the primary barrier to window operation (53.3%), followed by external noise (20%) and lack of operable windows at individual workstations (20%). These demonstrate that climatic conditions and limited window accessibility reduced user interaction with the ventilation system. Despite windows being operable, the single-sided layout and high-level window positioning limited effective cross-ventilation, contributing to restricted airflow and reduced ventilation effectiveness during colder periods.

4 Discussion

This section presents a detailed analysis and interpretation of the findings obtained from the study. The results are examined to identify key trends and to discuss their implications in the context of occupant thermal comfort.

4.1 Measured IAQ and Perceived Comfort

Measured environmental parameters generally complied with thermal comfort and ventilation guidance for naturally ventilated buildings. Average CO_2 concentrations (725 ppm) remained below the 1000 ppm recommended thresholds, temperature (mean 23.4 °C) remained within the adaptive comfort range recommended in ASHRAE 55 (2023), and relative humidity remained within the recommended 30–60% range. However, air velocity (mean 0.048 m/s) was significantly below the perceptible comfort threshold of 0.15–0.25 m/s. Despite numerical compliance, 40% of occupants reported "stuffy or stale air," alongside symptoms such as fatigue and headaches, indicating a discrepancy between measured IAQ indicators and perceived comfort. The findings support adaptive comfort approaches in naturally ventilated buildings, where occupant perception and behavioural adaptation influence comfort beyond steady-state thermal parameters. This aligns with previous findings [7], who reported that ventilation performance in Scottish buildings may meet regulatory thresholds while still failing to satisfy occupants due to airflow distribution limitations. Similarly, occupant perception is strongly influenced by air movement rather than pollutant concentration alone [17].

In contrast to studies demonstrating significant IAQ improvements through optimized natural ventilation [17], this study shows that compliance with CO_2 limits does not guarantee perceived freshness when air velocity remains low. These findings reinforce the importance of airflow distribution and air movement as determinants of comfort in naturally ventilated office environments.

Window operation behaviour significantly influenced ventilation performance. More than half of respondents identified cold weather as the primary barrier to opening windows. This aligns with previous finding that observed occupants in cold climates are reluctant to open windows due to thermal discomfort concerns [6]. Fobiri et al. (2023) similarly reported seasonal behavioural reluctance as a key limitation. In cold and variable climates such as Scotland, maintaining thermal comfort often takes precedence over air exchange. The findings demonstrated that ANV systems that depend on manual interaction underperform during colder periods. Climatic variability, including low outdoor temperatures and fluctuating wind patterns, further complicates airflow predictability and consistency, reinforcing the context-dependent nature of natural ventilation performance. The spatial configuration of Office which is single-sided high-level windows, lack of cross-ventilation pathways, and internal partitions restricted effective airflow distribution. Window opening produced negligible changes in air velocity, demonstrating architectural limitations rather than operational failure. This aligns with Evola and Popov (2006), who demonstrated that cross-ventilation effectiveness depends heavily on façade orientation and airflow pathways. It also supports findings by Lei et al. [18], who emphasized the influence of building configuration on pollutant dilution. This finding highlights the importance of considering spatial airflow dynamics during the design or

retrofit of naturally ventilated office buildings, particularly in heritage-sensitive con-texts where façade modifications may be restricted.

The combined influence of restricted airflow, climatic variability, and inconsistent window operation demonstrates practical limitations of purely passive, occupant-dependent natural ventilation in Scottish office environments. To enhance both energy efficiency and occupant well-being, ventilation strategies must move beyond reliance on manual window operation. User-responsive systems incorporating automated controls, demand-based airflow adjustment, or hybrid support mechanisms may help compensate for behavioural and seasonal variability. Such adaptive natural ventilation design approaches can improve airflow consistency while maintaining thermal comfort, thereby supporting climate-resilient office environments in cold regions.

5 Conclusion

This study evaluated the real-world performance of adaptive natural ventilation (ANV) in a Scottish university office through a simultaneous environmental monitoring of temperature, CO2, relative humidity (RH), PM2.5 and PM10, air velocity, and occupant questionnaire surveys.

The results show that while measured parameters for temperature and CO_2 generally aligned with adaptive comfort guidance in ASHRAE 55 (2023), EN 16798–1:2019 and ventilation guidance in ASHRAE 62.1, the findings reveal a significant IAQ-Perception Gap. The technical root of occupant dissatisfaction was identified as stagnant airflow, with a recorded mean air velocity of 0.048 m/s well below the human perceptibility threshold of 0.1 m/s. This lack of air movement, coupled with 73% of respondents reporting Sick Building Syndrome (SBS) symptoms such as fatigue and headaches, confirms that regulatory compliance alone does not guarantee perceived comfort or healthy indoor environments. In the context of Scotland's cold climate, the IAQ-Energy Paradox remains a critical barrier. Occupant reluctance to operate high-level, single-sided windows during colder months to avoid localized draughts leads to localized dead zones and increased air age. To move toward a professional standard of climate-resilient ventilation, this research advocates a layered strategy that combines: 1) Automated Actuators that is sensor-driven window controls to bypass behavioural barriers; 2) User-Responsive Overrides to maintain occupant activity through manual controls; 3) Retrofit Interventions that Implement low-level windows or trickle vents to enhance airflow distribution in restricted heritage spaces. Future research should focus on long-term seasonal monitoring to further refine these automated triggers for optimal energy-efficiency and occupant well-being in cold-climate regions.

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Understanding Zero Carbon Building Implementation Through Actor-Network Theory (ANT) Lens

Simin Tavajoh(✉) and Govert Valkenburg

Norwegian University of Science and Technology, Trondheim, Norway
simin.tavajoh@ntnu.no

Abstract. The construction and operation of buildings account for more than one-third of global carbon emissions, making low- and zero-carbon initiatives essential for climate change mitigation. However, the implementation of such initiatives remains inconsistent. This suggests that challenges lie not only in technical design but also in how sustainability measures are implemented and negotiated within real project settings. This study examines how sustainability-related artifacts—such as calculation tools, energy models, and policy documents—shape the implementation of low-carbon building practices. An integrative literature review was conducted, focusing on case-based studies that apply Actor-Network Theory (ANT). The findings show that artifacts do not determine results on their own. Their effects vary across contexts and depend on how they are interpreted, used, and connected to other actors within networks. The same tool may lead to different outcomes depending on local practices. Processes such as black-boxing can strengthen trust in certain actors while limiting others' influence. Overall, the study shows that sustainability outcomes in building projects emerge from the dynamic interaction between actors and artifacts rather than from technical solutions alone

Keywords: Net-Zero buildings · Sustainable Transition · Actor-Network Theory · Science and Technology Studies (STS)

1 Introduction

Climate change has made it essential to reduce greenhouse gas and carbon emissions across all sectors, particularly in building construction and use, which are major contributors and account for more than one-third of global emissions [1]. In April 2021, the European Union introduced a plan to replace the nearly zero-energy building standard with a zero-emission building target by 2030, supporting its broader aim of becoming climate neutral in the long term. As a result, all EU Member States are required to put in place and strengthen national laws and regulations to cut emissions from buildings and ensure that their countries reach carbon neutrality by 2050 [2].

Although many policies focus on sustainability, problems often arise during their implementation. There is often a gap between what is planned in policy and what is actually carried out in practice [3]. Research also shows that sustainable building is not

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limited by a lack of knowledge, technology, or assessment tools. Instead, the main challenge is the difficulty of changing current practices and adopting new ways of working in order to apply these new technologies [4].

This shows that the challenge is not only technical but also social and organizational. This is where Science and Technology Studies (STS) can provide useful insights. One key point in STS is that it examines how scientific knowledge and technologies are shaped and formed within social contexts, and in turn contribute to the shaping of those contexts [5].

1.1 Theoretical Background

Actor-Network Theory (ANT) was developed within Science and Technology Studies in the late twentieth century. It is based on the idea that nothing exists outside the relations that produce it [6]. A network consists of actors, or "actants," both human and non-human, that shape processes such as innovation. Human actors influence networks through their interests and interpretations, while non-human actors shape them through their material properties and constraints [7].

Society and organizations are not made up of social relations alone; they also involve relations between texts, devices, buildings, and other material components and in our analysis, we should treat such relations as being of the same kind [8, 9]. Rather than offering broad explanations, ANT focuses on describing how these relations are formed in practice and how they hold together, or fail to do so [6].

A key concept in ANT is "translation," which refers to the process through which actors align interests, build connections, and create order. Through translation, actors and networks are transformed, and certain elements come to represent others [8]. Ideas and policies circulate more effectively when turned into artifacts, but these must align with new networks of actors and knowledge to lead to action. Whether this occurs depends on how problems are defined and whether actors can enroll others and gain support for the idea [10].

1.2 Research Question and Paper Structure

From ANT perspective, reality is produced through connections between human and non-human elements. To understand how these networks are formed and stabilized, it is important to examine how actants interact, enroll one another, and how intermediaries shape their relationships.

This paper examines how low-carbon building initiatives are implemented or constrained through the interactions among human and non-human actors. It explores how artifacts mediate sustainability in building projects, drawing on existing studies. Section 2 explains the search method and the criteria used to select and assess the material. Section 3 presents and categorizes the collected data according to the main artifacts identified, followed by a discussion of the key findings and concluding remarks.

2 Method

2.1 Research Design and Data Collection

Given the focus of this study on cases that examine the success or failure of sustainable practices through the lens of Actor-Network Theory, an integrative literature review was chosen as the most appropriate method for data collection and analysis. An integrative literature review is a research approach that examines, evaluates, and brings together key studies on a specific topic in a unified way [11]. This type of review does not aim to include every published study on the topic. Instead, it involves a more flexible and selective approach, bringing together insights from different fields and research traditions to build a broader understanding [12].

Scopus was chosen as the main database for this study because it is well known for its wide coverage and for offering reliable and high-quality research from different academic fields [13]. The research questions were translated into a search string using Boolean operators. The search included terms such as "actor network" combined with "sustainabl*" OR "low carbon" OR "zero carbon," and "building" OR "construction."

2.2 Searching Process and Selection Criteria

The process of identifying relevant materials was carried out in two main stages. First, structured search strings were used to search electronic databases. After this step, additional sources were added to strengthen the data collection. These included references from selected articles, studies already known to the author, and AI-based tools such as Research Rabbit, which supported forward and backward citation tracking by grouping related studies.

Papers were selected based on inclusion criteria developed to ensure relevance to the research question.

- First, the study had to use Actor-Network Theory as an analytical lens to examine real case studies or practical examples.
- Second, the case study needed to be related to the building industry, or the analysis had to be clearly applicable to it. Some publications were excluded because they used the term "construction" in a different context.
- Third, the practices discussed in the papers had to relate to sustainability-oriented changes or the analysis had to be clearly applicable to it.

In addition, only studies published within selected subject areas were considered, with the search mainly limited to the fields of environmental studies, social sciences, engineering, and business

After the final two screening stages, 17 papers were first selected based on the relevance of their abstracts—9 from the first stage and 8 from the second. However, 5 of these were later excluded as they were found to be irrelevant (not aligned with all three inclusion points above). This led to a final sample of 12 papers for detailed review and data extraction. The full process is illustrated in Fig. 1.

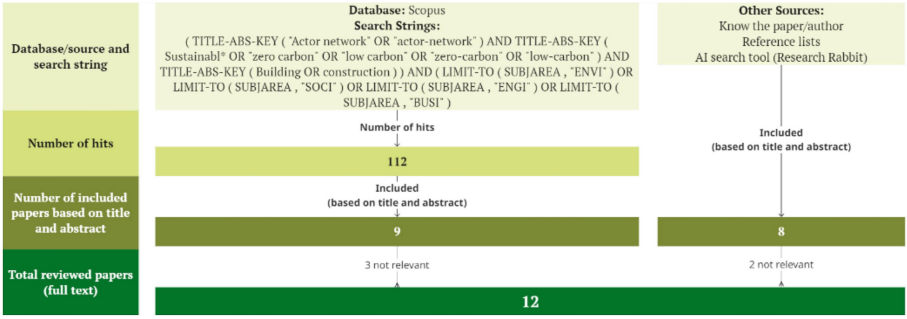


Fig. 1. Searching process

3 How Artifacts Meditate Low Carbon Initiative Implementation

The reviewed papers show that artifacts are crucial in shaping sustainable design work, both by enabling certain practices and limiting what actors can do. To clarify these patterns, the most frequently discussed artifacts are grouped into three categories in the next sub-sections.

3.1 Policy, Regulations, and Standards

Artifacts that comply with standards reinforce the dominant norms of a field because the value attached to compliance encourages others to follow, creating stability [14]. Based on the case study by Faulconbridge et al. [14] in commercial office design, this dynamic is evident in both the informal idea of Grade A offices—rooted in shared assumptions about what makes a marketable building—and the formal BCO (British Council for Offices) specifications, which translate these assumptions into detailed technical benchmarks. Together, these standards define what counts as a high-quality building, shape market expectations, and make designs comparable. At the same time, they restrict design agency by turning complex questions into fixed criteria, shifting attention away from how people actually work in offices and toward meeting predefined technical requirements. This promotes a uniform, one-size-fits-all approach, such as designing for occupancy levels far higher than most offices ever reach, which leads to oversized systems and limits the feasibility of low-energy solutions. In effect, those taken-for-granted standards "black-box" many aspects of design: they simplify complexity but also narrow professional judgment, diminish contextual knowledge, and lock in design choices that may not align with real patterns of use. In ANT terms, black-boxing means that certain objects, relations, and practices are made present while others become absent, forgotten, or displaced [15].

Relationships between artifacts and agencies vary between cases, and we see that different national policies engender different constellations. For example, in Cyprus [16], sustainability policies are broad and unspecific, giving building designers considerable interpretive freedom. Because formal criteria are limited, advances in areas such as energy performance or sustainable community design have largely depended on individual designers' expertise, motivation, and ability to persuade colleagues. However, Rydin

[17] showed in the context of planning for low-carbon urban development in London that planning documents influence how actors interact within the planning system, and this influence depends largely on the level of detail they contain. As policies specify exactly how to assess energy use, emissions, or technology options, they direct how planners interpret requirements and reduce the scope for discretionary decision-making. Such detail also strengthens the capacity of higher-level authorities to steer local planning practice from a distance. Rather than enabling flexible judgment, highly prescriptive wording can narrow planners' choices and limit the agency of those responsible for applying the policies.

3.2 Certificates and Database

Goulden et al. [18] show that the growing policy appeal of green building certification, as we saw in the Israeli case, stems from the assumption that certified buildings automatically reduce greenhouse gas emissions, even though actual environmental improvements are rarely measured. Israel's voluntary green building standard, SI 5281, awards points across categories such as energy, water, materials, health, waste, and transport, with buildings certified on a one- to five-star scale. This black-boxed understanding encourages adoption for reasons that extend beyond verified performance: the multi-category checklist makes certification a flexible and indirect indicator of environmental benefit, offering limited evaluation of performance in any single area, including energy. As a result, SI 5281 provides little evidence of real efficiency gains, yet its ambiguity enables it to circulate easily across governance settings, serving both energy-focused and broader environmental agendas.

Francart et al. [16] show a similar dynamic in Cyprus, where building designers rely on the single sustainability score provided in product databases rather than assessing underlying data themselves. This reliance leads many to assume that a high score signals low climate impact, even though the database primarily evaluates local environmental and human-toxicity indicators and includes energy use and climate impact only as optional information. Because the assessment is simplified and outsourced, it shapes which aspects of sustainability are considered and which are overlooked, turning the database into a black-boxed authority that effectively defines which materials are treated as "sustainable." In practice, users engage with the score much like they engage with a certification manual: its apparent clarity and ease of use guide decisions, while the criteria behind it remain largely invisible.

As mentioned earlier, applying for a sustainability certificate does not directly improve a building's environmental performance, but, according to Frank et al. [19], in Denmark, it indirectly encourages more sustainable choices throughout the design process. Economic incentives—such as reduced energy use and the durability of long-lasting materials—reinforce this effect, while costly analyses can be replaced with templates and checklists to keep certification accessible, which was introduced in the study as an added intermediary to reduce costs and make the process more standardized. The certification manual functions as a key non-human actor: its clarity and usability shape how homeowners, architects, and builders engage with the scheme. A manual that is too dense discourages participation, while one that is too flexible leaves less experienced builders vulnerable to pressure from actors motivated more by cost than environmental

goals. For this reason, the criteria must be strict enough to ensure genuinely sustainable outcomes, yet flexible enough to allow innovation within the standardized system and avoid black boxing.

3.3 Assessment Tools and Energy Modeling

The case study by Eidenskog [15] demonstrates how design challenges arose from the project's reliance on energy consultants and the limited transparency of their modeling tools. The initial energy model (IDA ICE), although presented as accessible, effectively functioned as a black-boxed instrument, since the consultant provided only simplified outputs that prevented other professionals from examining underlying assumptions. When a new energy consultant later introduced a spreadsheet-based model, its results diverged significantly from those of IDA ICE despite using identical input data. This discrepancy created uncertainty about which model was credible and revealed, at a late stage, that the building's projected energy performance was insufficient. Since the earlier modeling process had not allowed the team to scrutinize or test assumptions independently, they were unable to identify these issues during the phase when design parameters were still flexible. The resulting design challenges thus stemmed from the interplay between opaque modeling practices and the professionals' dependence on consultants for understanding and validating energy performance. This dynamic reflects a broader concern identified by Rydin [17]: planners and other professionals must possess, or have access to, sufficient modeling competence to challenge results when necessary. Without such capacity, they become dependent on consultants' interpretations, increasing the likelihood that modeling practices will become fully black-boxed and reducing their influence over how energy performance is defined and negotiated in development processes.

Georg [10] examined how an assessment tool shaped professional practice, which was developed with the aim of translating the idea of a sustainable city. The study shows that such calculative instruments influence collaboration and decision-making by defining what counts as relevant knowledge. Under tight competition deadlines, teams divided the tool's indicators along disciplinary lines, which turned it primarily into an intermediary for coordinating tasks rather than a shared analytical framework. While some professionals viewed the numerical scores as persuasive, most used the tool pragmatically as a checklist to ensure compliance with client requirements, without allowing its benchmarks to guide their design vision. A smaller number of teams engaged with the tool more strategically, using its parameters to reassess priorities and revise design concepts, whereas others dismissed it as too restrictive for more qualitative ambitions. Across these varied uses, the tool functioned mainly as an intermediary that facilitated coordination, but in some cases also acted as a mediator that reshaped knowledge, design choices, and professional interactions.

4 Discussion and Conclusion

Sustainability requirements, definitions, and calculation methods are often inscribed in artifacts, and these elements can shape sustainable design and create opportunities to advance it. However, their influence depends on how they connect with the everyday

practices of local actors. From an Actor-Network Theory perspective, the focus is not on providing general explanations, but on examining how relations between actors and artifacts are formed, how they are stabilized, and how they sometimes weaken or fail. This helps explain why sustainability policies do not automatically lead to consistent outcomes in practice.

The reviewed studies indicate that the effects of artifacts differ across contexts and depend on their interaction with other actors and actants within the network. Even the same tool, used within the same national setting, was applied and interpreted in different ways [10]. This suggests that outcomes are not determined by the artifact itself, but by the network of relations in which it operates. Georg [10] argues, focusing only on professionals overlooks how artifacts enable or challenge collaboration. Flexibility in the use of artifacts may allow room for interpretation, but it can also leave less experienced actors exposed to pressure from others.

The concept of black-boxing illustrates how tools and documents can shape power relations. When artifacts such as energy models are treated as closed systems, they may increase trust in certain experts while limiting others' ability to question underlying assumptions [15]. Similarly, policy documents can act as intermediaries that structure authority; highly detailed language may restrict the role of some agencies, as seen in the UK case [17].

Overall, sustainability in building projects emerges not from technical tools alone but from ongoing interactions between actors, artifacts, and practices. The gap between policy goals and implementation reflects social and organizational dynamics as much as technical ones. ANT helps explain why sustainable building initiatives succeed or struggle by showing how networks of human and non-human elements shape outcomes and power relations. The literature indicates that these efforts work best when technologies fit local practices and when actors engage with one another around shared goals.

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Lifecycle Assessment, Metrics and Monitoring: Whole-Life Carbon, Embodied Energy, Circularity Indicators, Benchmarking Frameworks, Multi-criteria Decision-Support Methods, and AI/IoT-Enabled Lifecycle Monitoring

Comparative Lifecycle and Circular Economy Assessments of Railway Bridges: Concrete Bridge Versus Wrought Iron Viaduct

Naziul Islam[1], Charalampos Baniotopoulos[2], Diāna Bajāre[3], and Sakdirat Kaewunruen[4](✉)

[1] Network Rail, Milton Keynes MK9 1EN, UK
[2] Aristotle University of Thessaloniki, Thessaloniki 541 24, Greece
[3] Riga Technical University, Ķipsalas iela 6a, Riga LV-1048, Latvia
[4] The University of Birmingham, Birmingham B15 2TT,, UK
s.kaewunruen@bham.ac.uk

Abstract. This study employs a cradle-to-grave (A–D) life-cycle assessment over a 120-year reference period, utilizing a 1 m^2 deck functional unit, span-normalized for equivalent comparison, to evaluate the total greenhouse gas emissions throughout the life cycle of two railway bridge types: a historic wrought-iron viaduct and a reinforced-concrete underbridge. Two case-specific Life Cycle Assessment models are developed for the experiment, utilizing consistent UK factors, product-level data for materials, quantified transport and site plant metrics, activity-based operations and maintenance (coatings, membranes/joints, bearings, local strengthening), and explicit Module D credits from end-of-life recovery. The wrought-iron viaduct has a carbon footprint of 2.20 tCO_2e/m^2 (A–D), while the concrete bridge has a carbon footprint of 5.8 tCO_2e/m^2. The numerical findings are supported by module analyses and sensitivity assessments, which demonstrate that A1–A3 and end-of-life are the primary determinants. The principal conclusion is that, when feasible, the retention of wrought iron and focused renovation surpasses new short-span concrete in terms of whole-life carbon; for concrete, performance is contingent upon binder selection and B-stage strategy when membranes, joints, and bearing policy are comprehensively modelled. Low-clinker binders, integral/semi-integral abutments, waterproofing/joints with a lifespan of at least 40 years, EAF-route steel for reinforcement, and inspection-driven deconstruction exemplify effective practice levers that enhance engineering decisions, reduce total lifecycle costs and disruptions, and advance societal net-zero objectives.

Keywords: Circular Economy · Lifecycle Analysis · Systems Thinking · Carbon Inventory · Energy Inventory · Net Zero

1 Introduction

Bridges and viaducts are vital transportation infrastructure that cross urban and natural boundaries. They are critical infrastructures underpinning the growth of built environment. Strategically important designs often require over 100 years of longevity. Their

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lifespan comes with a high environmental cost: their material-intensive nature increases embodied carbon. Embodied carbon can make up over 60% of railway infrastructure's carbon footprint, according to [1]. Cement accounts for 8% of global CO2 emissions, and steel for 7% [2]. Development of sustainable building design and construction methods is crucial to decarbonizing rail transportation. The UK's net-zero transition needs the railway sector to address its infrastructure's high embodied carbon [1], which includes rethinking bridge design and material use.

The circular economy (CE) replaces the linear model of 'take-make-dispose' with the 10R principles of discard, rethink, recycle, and recover, as described by Koohmishi et al. [3], including R0 Refuse, R1 Redesign or Rethink, R2 Reduce, R3 Reuse, R4 Repair, R5 Refurbish, R6 Remanufacture, R7 Repurpose, R8 Recycle and R9 Recover. Material substitution, design for disassembly, modularity, adaptive reuse of substructures, and end-of-life material recovery can be applied to railway bridges. CE methods must not compromise structural performance; railway bridges must meet strict safety, serviceability, fatigue, and durability standards under operation. This study examines reinforced-concrete underpass bridges and wrought-iron viaducts in the UK rail network. They were chosen because they reflect diverse building eras and maintenance demands with variable whole-life carbon consequences.

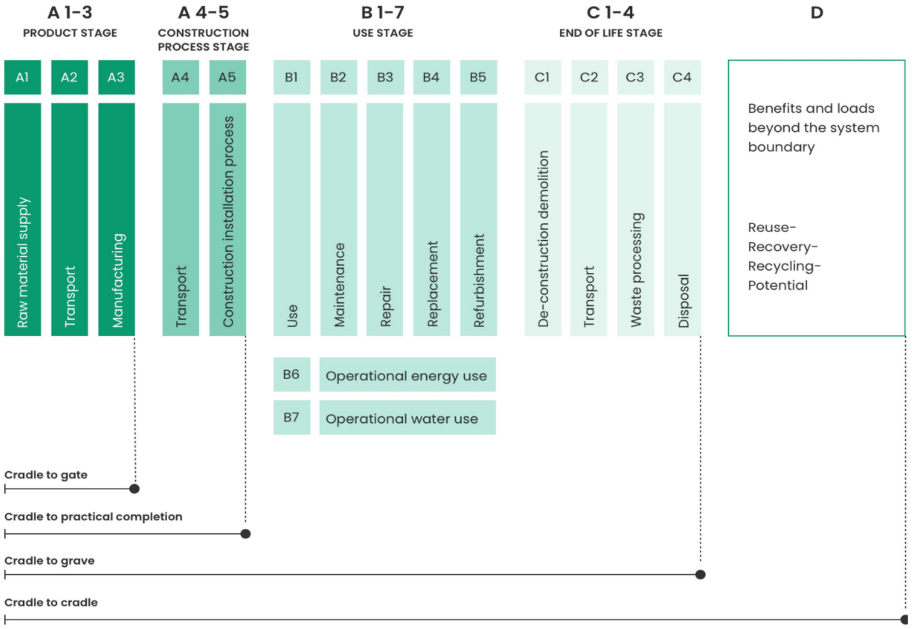


Fig. 1. Lifecycle stages and systems boundary of engineering assets.

Railway networks adopt many wrought iron and concrete structures, but their complete lifespan environmental performance has not been thoroughly assessed. This study tackles this gap by performing Life Cycle Assessment (LCA) of these two structures, focusing on their carbon emissions throughout the lifecycle, as shown in Fig. 1. This study

offers new findings by comparing each system's circular economy concepts, e.g. material recovery potential and design for adaptation, to decide which is more sustainable. The goal is to quantify and compare whole-life (A–D) greenhouse-gas emissions per 1 m^2 of deck for a historic wrought-iron railway viaduct and a reinforced-concrete under bridge over a 120-year period and to identify circular-economy interventions that reduce carbon without compromising Eurocode-compliant safety, serviceability, fatigue and durability. Comparing concrete and wrought iron bridge structures under the same functional unit will provide new discoveries and insights. Rail engineers will significantly benefit from co-design, planning, building, operation, maintenance, and end-of-life management of bridge infrastructures.

2 State of the Art Literature Review

Many wrought-iron railway viaducts in the UK are over 100 years old (e.g. in Sherrington). Ancient wrought iron viaducts follow circular economy (CE) principles of structural longevity, adaptive reuse, and material recovery. For transport network conservation, wrought iron is more ductile and fatigue-resistant than modern materials [4]. Wrought iron constructions can endure a century if maintained, demonstrating CE "design for longevity". Archives suggest that disassembled wrought iron components were reused in the 19th and early 20th centuries, starting the current cycle [4]. Medieval wrought iron production processes, material defects, and lack of standardization made large-scale reuse and recycling difficult. Retrofitting historic structures to current load and safety regulations may require steel strengthening or composite solutions, limiting cyclical advantages. Although difficult, wrought iron viaducts are noteworthy circular infrastructure examples of CE-aligned preservation, adaptive reuse, and modular disassembly.

Concrete bridges generally cause considerable initial embodied carbon; however, their extended service lives and little maintenance reduce their environmental impact, as indicated by lifecycle assessments. The incorporation of fly ash or GGBS decreases embodied emissions and enhances structural integrity [5]. Embodied carbon, along with energy associated with building operation, demolition, and recycling, is being incorporated into LCA frameworks. Recyclable concrete aggregates contribute positively to environmental sustainability. Numerous studies [5] indicate that concrete has a longer lifespan than steel; nevertheless, the studies primarily focus on A1–A3 phases, maintenance schedules, or specific mixtures. This reallocates responsibilities and enhances the advantages of "minimal intervention" at only design stage. However, local variables, environmental product disclosures, and durability-oriented B-stage modelling are not currently utilised to create bridge-specific, audit-ready A–D life cycle assessments per square meter. In order to promote circular economy initiatives (e.g., low-clinker mixtures, membranes/joints with a 40-year lifespan, design for deconstruction), LCA evaluations should consider both with and without Module D.

Most previous research on wrought-iron viaducts targeted B-stage repainting/strengthening using mild-steel proxies for A1–A3, partial boundaries (typically A1–A3), without considering Phase D. They adopted generic intervals instead of ISO 12944

or product/condition data. Often, there is no per-m^2 functional unit, span normalization, or consistent factor sets across A-D stages. Circular solutions like SCMs, high-grade recycled aggregate, and modular precast are generally considered separately from a whole-life system boundary. These limitations make it difficult to compare smaller A1–A3 combinations to larger B-stage treatments or concrete D credits to metal D credits. They also make it difficult to renovate, replace, buy, and report under PAS 2080. Thus, this study fills the gap by comparing lifecycle outputs per square meter between a wrought-iron viaduct and a reinforced-concrete underbridge. UK-relevant parameters (DEFRA/DESNZ for transport, fuels, and waste; ICE/EPDs for A1–A3), durability-based B-stage modelling, and with- and without-D reporting are fully considered. This allows quantitative evaluation of circular-economy solutions. Engineers in practice can utilise our outcomes to achieve net-zero targets.

3 Research Methodologies

This study applies a cradle-to-grave LCA structured to ISO 14040/14044 and EN 15978 [6, 7], with the functional unit (e.g. unit capacity), system boundary (e.g. right of way), and reporting (per-m^2 FU, span normalisation, and A–C/A–D disclosure) aligned with other studies [2]. This study follows ISO/EN 15978 and 14040/14044 [6, 7]. A1–A3 (product stage), A4 (transport to site), A5 (construction/site energy), B2/B4/B5 (maintenance, replacement, strengthening), C1–C4 (deconstruction, transport, processing, disposal), and D (circular practices) are modules covered. Inactive bridge decks have no operating energy or water consumption, hence track/rolling-stock operation is excluded from B6/B7. The study spans 120 years. Data is supplied in tCO_2e using GWP-100 factors and presented in both A-C and A-D formats for clarity. The single-track bridge's functional unit (FU) is 1 m^2 of deck plan area (length × clear deck width), following best practices for FU discipline and boundary clarity [2]. Multiplexing by the clear deck width yields per-metre data in this FU, which avoids width/span bias and follows whole-life reporting norms. DEFRA/DESNZ (transport, fuels, waste), ICE, and product EPDs for A1–A3 together with peer-reviewed infrastructure LCA studies and the project BoQ are primary data sources.

3.1 Recycling and Decommissioning

Inspection and condition monitoring guide selective deconstruction at end-of-life comprises cover/chloride profiling, half-cell/corrosion-rate assessments, ultrasonic/GPR rebar and thickness measurement, and fatigue hotspot identification with SHM. This helps us plan for design-for-deconstruction (DfD) and determine which parts may be reused, refurbished, or recycled well using circular economy principles. The wrought-iron viaduct recycles 95–100% of ferrous mass for secondary steel, resulting in a 0.1–0.2 tCO_2e/t recycling burden. Masonry components are increased for secondary usage. Deconstructing a concrete bridge generates 15–25 $kgCO_2e$ per ton of concrete. Between 50–70% is converted into RA1/RA2, yielding 20–40 $kgCO_2e$ per ton in substitution credits. The rebar should be fully recycled. About 20% of building energy comes from demolition fuel. According to EN 15978 [6], Module D provides beyond-boundary benefits.

Each stage of the 10R hierarchy is supported by inspection data and deconstruction plan: Reject (avoid too much detail); Reevaluate (integral/semi-integral abutments to remove bearings); Minimize (low-clinker compositions, streamlined sections); Repurpose (removable parapets, plates, and masonry blocks); Restore (targeted coating/patching to prolong life); Revamp (grit-blast and recoat ironwork and add a new coating to RC decks); Remanufacturing recycles iron and steel into new parts. Utilize unused parts. Recycling (high-yield metals, quality-assured RA1/RA2) and energy recovery from non-recyclable waste are two ways. Implementing 10R in this way maximizes retained value and clarifies Module D's high metal recovery and reliable concrete replacement.

3.2 Case Study I: Wrought Iron Structure

Sherrington Viaduct, an 1887 five-span, two-track underbridge, with three wrought-iron longitudinal main girders each span with cross-bracing. Spans 1 and some of 2 and 5 have filler-beam decks, whereas 3 and 4 have steel transverse troughing, as shown in Fig. 2. Later Victorian buildings followed Board of Trade railway company rules and used allowable-stress procedures. British standards did not apply in 1907 since BS 153 Steel Girder Bridges was not created until the early 1920s. The current design for upgrade follows Eurocode 3, incorporating Eurocode 2 and fatigue requirements for wrought iron material qualities determined by testing and conservative characteristic values, and maintenance scenario (re: NR/L2/CIV/032).



Fig. 2. Sherrington Viaduct

3.3 Case Study II: Concrete Structure

The structure located between Brixton Junction and Denmark Hill Station. It elevates railway traffic above a pedestrian street, as shown in Fig. 3. The initial design process was unspecified. A precast concrete ballasted deck and edge panels have been added to ATL and UP Cat lines. Slab track decks make up the UP Cat. Unaltered CAT lines have concrete infill panels supported by wrought iron girders. The design and assessments are based on Eurocode 2 with actions from Eurocode 1 considering standardized execution,

durability requirement and maintenance scenario (re: NR/L2/CIV/032). Where fitted, components, bearings, and deck waterproofing/joints comply with rail specifications. Maintenance assumptions reflect standard practice that involve re-waterproofing, joint renewal, bearing replacement and predictive inspections to manage deterioration and defer heavy interventions. These parameters are Eurocode-consistent and form the basis of the LCA modelling in this study.



Fig. 3. Cambria Rd. Under Bridge. Note: both case studies adopt identical FU and boundaries.

4 Results and Discussions

The total lifecycle GHG emissions are assessed for both structures, shown in Table 1. Cambria Rd exhibits A1–A3 emissions of 2.88 tCO_2e/m^2, whereas Sherrington demonstrates A1–A3 emissions of 2.81 tCO_2e/m^2. Sherrington possesses a little advantage since, although ferrous materials have a higher factor per tonne, the metal mass per square meter is less than the concrete volume per square meter in Cambria's slab method, and the preserved historic fabric does not contribute additional A1–A3 emissions. The clinker content and slab quantity regulate Cambria's Material production and manufacturing phase (MRMP) in practice. The tonnage of newly introduced steel such as strengthening or secondary steel and the designated steel production method (EAF versus BOF) are the primary considerations for Sherrington's MRMP. As shown in Fig. 4, if A1–A3 are allocated to the heritage fabric instead, Sherrington's MRMP would increase by that amount. This is why the boundary assumption (e.g. right of way and sub-systems layers of bridge structures) must be clearly defined.

Cambria Rd. has much greater C&T impacts compared to Sherrington A4–A5 0.377 tCO_2e/m^2, approximately 6.5% of its A–D. The disparity arises from the greater transported tonnage and site plant energy associated with reinforced concrete compared to the wrought-iron example, which involves far less new work. A4 freight scales proportionally with haul distance, therefore, longer supply chains would exacerbate the disparity. Nonetheless, the A5 plant remains unaffected by distance and continues to be the most significant C&T component for RC. The most effective method to diminish emissions is through local sourcing, rail-barge freight, and electrified or HVO facilities, with a primary emphasis on material decarbonization. Further analysis indicates that the

Table 1. Life cycle assessments of Sherrington Viaduct and Cambria Rd. Under Bridges

Lifecycle stage	Sherrington Viaduct (tCO_2e/m^2)	Cambria Rd UB (tCO_2e/m^2)
Material production and manufacturing	2.806	2.880
Construction and Transport (C&T)	0.031	0.377
Operation and maintenance (O&M)	0.172	0.017
Recycling and Decommissioning (R&D)	−0.809	2.493
Total	2.200	5.767

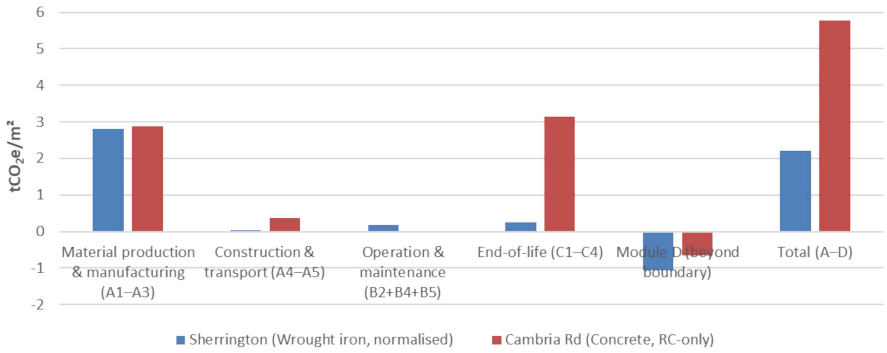


Fig. 4. Comparison of whole-life carbon emissions between wrought-iron and concrete bridges

Sherrington wrought iron viaduct possesses a greater operating and maintenance (O&M) carbon footprint of around 0.172 tCO_2e/m^2. This is primarily due to coating renewals and restricted structural repairs. Conversely, the concrete bridge (Cambria) exhibits a significantly lower value of approximately 0.017 tCO_2e/m^2. This is since it merely entails substituting the bearings, rather than requiring significant ongoing maintenance such as refilling the membrane and joints.

Sherrington viaduct demonstrates RDP − 0.809 tCO_2e/m^2. In contrast, Cambria Rd RDP at 2.493 tCO_2e/m^2. The difference stems from Sherrington's substantial metal recovery compared to little concrete credits, where even quality-assured RA1/RA2 substitution only partially mitigates the costs of demolition and processing. To secure the wrought-iron credit and improve the concrete outcome, the deconstruction must be directed by inspections. Mid-life structural health monitoring, NDT, and condition assessment (GPR for rebar configuration, cover/chloride profiling, half-cell/corrosion-rate analysis, thickness/rivet evaluations, ultrasonic pulse velocity) ascertain components amenable to reuse or remanufacturing, segregate uncontaminated concrete for premium

recycled aggregate, and formulate selective extraction methodologies to avert contamination and downcycling. Integrating materials/product passports (steel grades, coating specifications, mix/EPD identifiers), DfD details and a C-stage process statement boosts recovery rates and diminishes demolition fuel use, hence swiftly increasing C and D results. The instruction is to Reduce, Repair, Refurbish, and Reuse before Recycling or Recovering, in accordance with circular economy (10R) principles. For Sherrington, this maintains substantial metal credit, but for Cambria, it improves quality of aggregate and amplifies the minimal concrete substitute benefit.

5 Conclusions

This study offers a comparable, per-square-meter and span-normalized whole life cycle assessment of two prevalent railway bridge typologies in the UK. Throughout a 120-year span, the wrought-iron viaduct exhibits around 2.20 tCO_2e/m^2 (A–D), whereas the reinforced-concrete underbridge demonstrates approximately 5.77–5.81 tCO_2e/m^2 (A–D), thereby strongly advocating for the preservation and selective refurbishment of wrought-iron where structurally viable. The results yield specific actions: for low-clinker concrete mixes, (i) implement waterproofing/joints with a lifespan of >40 years, (ii) ensure effective drainage, and (iii) utilize integral/semi-integral abutments to mitigate both A1–A3 and B; for wrought iron, (i) reduce new metal tonnage, (ii) employ EAF-route steel for reinforcement, and (iii) plan inspection-driven deconstruction (materials passports, DfD) to maintain the D-credit. These strategic actions reduce carbon emissions and costs while maintaining safety performance, enabling net zero with minimal inconvenience to passengers and the public.

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Identifying Accurate Growth Models for Biogenic Carbon Uptake of Wood in Dynamic LCA

David von Dufving[1,2(✉)], Marijke Steeman[1], and Liselotte De Ligne[2]

[1] Department of Architecture and Urban Planning, Ghent University, Ghent, Belgium
david.vondufving@ugent.be

[2] Department of Environment, Ghent University, Ghent, Belgium

Abstract. Trees store biogenic carbon, which, when retained in wood products, can temporarily contribute to climate change mitigation. Dynamic Life Cycle Assessment increasingly accounts for this temporary storage by quantifying its "climate change–biogenic" impact using the Global Warming Potential (GWP) indicator. While current dLCA approaches model the timing of carbon storage and release, a standardized approach for representing tree growth, and thus carbon sequestration, remains lacking, causing significant variability in results. Existing practice typically applies either a growth approach, where sequestration is modelled as a negative pulse emission at harvest, or a regrowth approach, where sequestration occurs gradually as replacement trees grow. As various regrowth models are employed in contemporary dLCA studies, this study compares one growth model (G_G) and three regrowth models: (i) a Gaussian distribution (R_GD), (ii) the Chapman–Richards function (R_CR), both commonly used, and (iii) a newly proposed model based on Net Annual Increment data from national forest inventories (R_NAI). The four models are applied to calculate the GWP100 climate change–biogenic impact of stem wood for two hardwood and two softwood species used in timber construction in Germany. Results suggest that the NAI regrowth model captures growth dynamics most detailed, but its high data requirements and questions about its data validity raise questions about scalability and practical implementation. Regardless of model, the hardwoods offer a higher temporary carbon sink potential, thus offering a possible environmental incentive to promote the use of hardwoods in long-lived construction products.

Keywords: Biogenic Carbon · dynamic Life Cycle Assessment · Carbon Storage · Bio-based Building Materials

1 Introduction

To meet the EU target of climate neutrality by 2050, temporary carbon removals are increasingly seen as essential (European Commission, 2025). However, despite the growing interest in crediting the temporary storage of biogenic carbon, there is still no scientific consensus on how to incorporate this effect into dynamic Life Cycle Assessment (dLCA) (European Commission, 2024). This uncertainty has led to diverse modelling approaches, raising concerns about robustness, and practical usability of dLCA.

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The Horizon Europe *WoodStock Project* addresses these challenges by developing a robust and transparent LCA framework for (underutilised) wood products (WoodStock Project, 2024). In line with the WoodStock objective of incentivizing sustainable forest management and underutilised wood streams, including hardwood and post-consumer wood, the project adopts the dynLCA framework of Levasseur et al. (2010), regarded as one of the most detailed and reliable dLCA methods (Hoxha et al., 2020). Nonetheless, key uncertainties remain regarding the timing of biogenic carbon sequestration.

Several approaches for determining the timing of biogenic carbon sequestration have been proposed in literature. For example, Peñaloza et al. (2016) explored a "growth approach", where biogenic carbon sequestration is assumed to occur prior to harvest and is thus modelled as a negative pulse emission at harvest. In contrast, the "regrowth approach" assumes that harvest creates a carbon debt, which must be gradually re-sequestered through the growth of a replacement tree. Applying this second approach requires modelling how sequestration unfolds over time rather than treating it as an instantaneous event. Three different regrowth models are thus analyzed alongside the growth model (G_G). Two common regrowth models, namely the "Gaussian Distribution" (R_GD) and the "Chapman-Richards" (R_CR) function, as well as a newly proposed model based on the Net Annual Increment (R_NAI) growth derived from national forest inventories. This study aims to compare both approaches to determine which is best suited for use in the context of underutilised wood. The comparison between the different regrowth models furthermore aims to offer insights into the robustness of the R_NAI model, which could offer species-specific growth curves.

2 Methodology

2.1 Research Steps

To exemplify the effect of the different models, a product life-span of 100 years was assumed for stem wood of four common European tree species (*Picea abies* (PA), *Pinus sylvestris* (PS), *Quercus robur* (QR), and *Fagus sylvatica* (FS)) were chosen as example cases. In a first step species-specific biogenic carbon contents were derived based on von Dufving et al. (2026a) (711.3 $kgCO_2/m^3$ for PA, 826.1 $kgCO_2/m^3$ for PS, 1056.19 $kgCO_2/m^3$ for FS, and 1140.5 $kgCO_2/m^3$ for QR). For the growth model the negative biogenic carbon content was then inventoried for the year of harvest (year 1). This simplification is needed to assess the impact of the growth and the regrowth models over the same Time Horizon. For the regrowth models, the biogenic carbon content was allocated over defined regrowth time frames, representing the time it takes to re-sequester the biogenic carbon. The regrowth time frame of each species (39 years for PA, 37 years for PS, 52 years for FS, and 65 years for QR) was calculated based on NAI data, expressing biomass accumulation until the functional unit of $1m^3$ stem wood is regrown (von Dufving et al. 2026b). Afterwards, annual dynamic characterization factors for a 100-year Time Horizon, based on Resch et al. (2021), were applied to calculate GWP-biogenic.

2.2 Growth and Regrowth Models

The G_G model allocates the carbon uptake as a pulse emission in year 1, equal to the negative biogenic carbon content. The growth curve of the R_GD model is calculated according to Eq. (1) and normalized so that the total carbon sequestration equals the carbon content (Cherubini et al. 2011).

$$f(x) = \frac{A}{\sqrt{2\pi\sigma 2}} e^{-\frac{(x-\mu)2}{2\sigma 2}} \tag{1}$$

μ = mean = regrowth time frame/2
σ = standard deviation = mean/2
A = biogenic carbon content

The R_CR model is also commonly employed using its first derivative and is stipulated in Eq. (2) and normalized in Eq. (3) For the shape parameters k (0.023) and p (Levasseur et al., 2010), fixed values based on Resch et al. (2021) were employed.

$$f_{CR}(y) = kpe^{-ky}\left(1 - e^{-ky}\right)^{p-1} \tag{2}$$

k = variable growth rate parameter
p = variable catabolism parameter

$$f_{bio,i\ (y)} = m_{CO_2,i} \cdot f_{CR}(y) / \sum_{y=0}^{RP} f_{CR}(y) \tag{3}$$

$m_{CO2,i}$ = biogenic carbon content of inventory product

The R_NAI model uses Net annual increment data (in in m^3 ha^{-1} $yr.^{-1}$) to model growth curves. This study draws on the publicly available "Volume_increment_database" by (Pilli et al., 2024) which reports species-specific NAI data at a regional level, based on harmonized data reported by the latest available National Forest Inventories of each country. For this study averaged data from Germany were chosen, as extensive data entries are available for all four relevant tree species. Utilizing the same formula which was employed to calculate the regrowth time frames based on von Dufving et al. (2026b) (Eq. 4), annual growth values, which are then multiplied with the negative carbon content, can be computed.

$$\sum_{i=1}^{t} \left(\frac{A}{f}\right) * NAI_i = 1 \tag{4}$$

A = the production area in ha, e.g. 15 $m^2 f$ = the fraction of the area used for the biomass, e.g. 0.75 for stem of softwood, 0.7 for stem of hardwoodNAI_i = Net Annual Increment of the biomass in m^3/ha/y for year i. (To normalize the total growth to 1, the growth value of the last year was manually constrained.)

3 Results

3.1 Annual Biogenic Carbon Sequestration

This results section compares the annual biogenic carbon sequestration values as inventoried during the Life Cycle Inventory phase. When comparing the different growth models with each other it becomes apparent that annual biogenic carbon sequestration varies significantly across the four modelling approaches (Fig. 1).

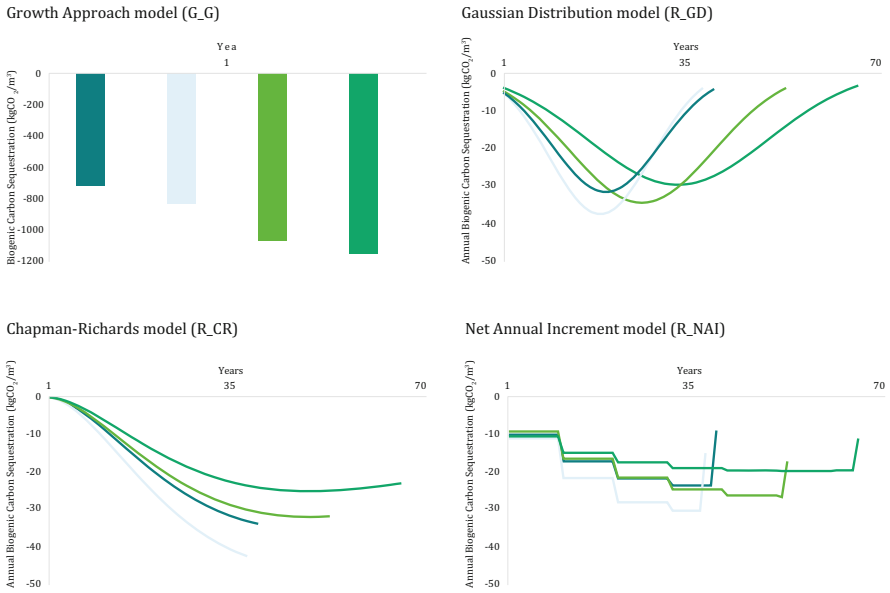


Fig. 1. Line Diagram showcasing the annual biogenic carbon sequestration value in kgCO2/m^3 for 1m^3 for selected European tree species (PS: light blue, PA: dark blue, FS: light green, QR: dark green) and growth models.

The G_G model assumes that the total carbon sequestration occurs in the first year. In contrast, all regrowth models gradually distribute sequestration over the defined regrowth time frames. The R_GD model assumes a symmetrical distribution of sequestration, peaking precisely at the midpoint and tapering off evenly on both sides. When employing this model, all species thus follow the same pattern, only more stretched or condensed depending on the species. The R_CR model portrays sequestration as a continuous curve that typically peaks in the early stages of the rotation, depending on the specific values of its shape parameters k and p (48 years for the parameters chosen in this study). The R_NAI model, by contrast, estimates sequestration based on biomass growth dictated by age classes (e.g., in 10-year intervals), resulting in a stepped profile. This approach generally shows a flatter peak in sequestration before the midpoint of the rotation period and then slowly tapers off. Furthermore, all species exhibit a lower annual biogenic carbon sequestration value for their last year, due to the requirement of total biogenic carbon sequestration equaling the biogenic carbon content.

3.2 GWP-Biogenic

This section compares the effects of the diverging growth curves and biogenic carbon sequestration values on GWP-biogenic. When comparing the GWP-biogenic score of the same species across models, species-specific differences become apparent (Table 1). For PA, biogenic carbon sequestration averages $-621.85 \pm$ a standard deviation of 62.06 $kgCO_2/m^3$, exhibiting an on average 30% lower GWPbio score than QR. For PS, biogenic carbon sequestration averages -727.11 ± 68.72 $kgCO_2/m^3$, exhibiting an on average 18% lower GWPbio score than QR. For FS, biogenic carbon sequestration averages -873.74 ± 125.35 $kgCO_2/m^3$, exhibiting an on average 2% lower GWPbio score than QR. For QR, biogenic carbon sequestration averages -895.2 ± 167.35 $kgCO_2/m^3$. In summary, the order of GWP-biogenic scores between species within the same model is generally constant, irrespective of which model was chosen. Across the models QR showcases the highest average temporary carbon sink potential followed by FS, PS, and PA.

When comparing the GWP-biogenic score of the same model across species, model-specific differences become apparent. When employing the G_G model, biogenic carbon sequestration averages -933.53 ± 199.02 $kgCO_2/m^3$ and GWPbio values on average are 27% higher than those for the R_NAI model. When employing the R_GD model, biogenic carbon sequestration averages -758.7 ± 116.85 $kgCO_2/m^3$ and GWPbio values on average are 4% higher than those for the R_NAI model. When employing the R_CR model, biogenic carbon sequestration averages -696.41 ± 97.16 $kgCO_2/m^3$ and GWPbio values on average are 4% lower than those for the R_NAI model. When employing the R_NAI model, biogenic carbon sequestration averages -729.24 ± 106.27 $kgCO_2/m^3$. In summary, the order of GWP-biogenic scores between models within the same species are generally constant, irrespective of which species was chosen. Across the species the G_G model showcases the highest temporary carbon sink potential followed by the R_NAI model, the R_GD model, and the R_CR model.

Table 1. GWP-biogenic in $kgCO_2/m^3$

Species	G_G	R_GD	R_CR	R_NAI
PA	−711.3	−611.92	−569.99	−594.2
PS	−826.1	−717.35	−611.92	−694.57
FS	−1056.19	−851.41	−777.44	−809.91
QR	−1140.54	−854.14	−767.82	−818.32

4 Sensitivity Analysis

A sensitivity analysis was conducted to assess the robustness of the R_NAI's NAI data and its effect on the resulting GWP-biogenic values. For this purpose, NAI data for the same previously selected species were retrieved for France and compared with the

corresponding results from Germany. The objective was to determine whether country-specific differences change the results significantly. To ensure comparability between countries, the same species-specific biogenic carbon contents used for Germany were applied to the French dataset. However, because the NAI values differ between the two countries, new regrowth time frames had to be calculated for each species based on the same methodological approach described earlier. The resulting regrowth periods for France were 40 years for *Picea abies* (PA), 98 years for *Pinus sylvestris* (PS), 83 years for *Fagus sylvatica* (FS), and 106 years for *Quercus robur* (QR). Compared with the German NAI data, the French regrowth time frames are generally longer, though the magnitude of this difference varies considerably across species (see Fig. 2). The shape of the growth curves over time also diverges. For multiple species the German data indicate a continuously increasing growth rate, in contrast to the more linear and overall decreasing trend observed for France. These differences also have significant implications for GWP-biogenic. While the average GWP-biogenic score across the selected species for the German dataset is -729.3 kg CO_2/m^3, the French dataset exhibits an average of -615.57 kg CO_2/m^3 for the same species, representing a reduction of approximately 16%. However, this effect is not consistent across species, with results ranging from an increase of $+17\%$ for PA to a reduction of -38% for PS.

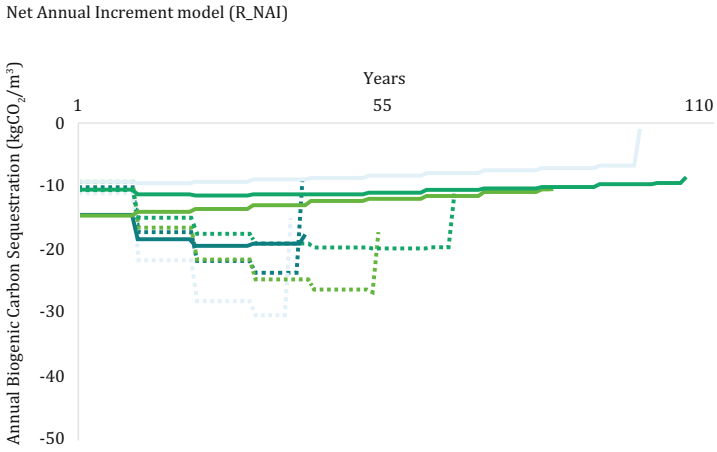


Fig. 2. Line Diagram showcasing the annual biogenic carbon sequestration value in kgCO2/m^3 for selected European tree species based on NAI FR (solid line) and NAI DE data (dotted line) (PS: light blue, PA: dark blue, FS: light green, QR: dark green)

5 Conclusion

This study compared four growth models for dynamic LCA with the aim of identifying a suitable approach to calculate GWP-biogenic of long-lived timber products. Given WoodStock's objectives and consistent with findings from literature, post-harvest regrowth models appear preferable to the growth model because they provide more conservative estimates and support incentives for continued forest regeneration. Among the

evaluated regrowth approaches, the R_NAI model offers the highest level of detail and transparency due to its direct reliance on national forest inventory data. Assuming these data are robust, both the R_CR and R_GD models provide reasonable approximations when NAI data is unavailable or deemed overly complex. R_CR may be preferable when a more conservative estimate or species-specific parameterization is required, whereas R_GD offers the most accessible implementation. Across the models, QR exhibited the highest average temporary carbon sink potential, followed by FS, PS, and PA. This suggests a potential environmental incentive to expand the use of selected hardwoods in long-lived construction products to increase the construction industry's climate change mitigation potential.

The study also highlighted several limitations with the sensitivity analysis. While it was not within the scope of this research, to validate the underlying NAI data, the high deviation in growth curves and subsequent GWP-biogenic results within the same species between Germany and France seem significant. Therefore, future research should focus on simplifying the NAI regrowth model, to minimize the risk of unreliable data.

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Life Cycle Assessment of Wood-Based Panels Considering Recycling Potential in Circular Construction

Mehmet Eren Şahin[1(✉)], Hülya Kalaycıoğlu[2], and Uğur Aras[2]

[1] Kastamonu Integrated Wood Industry and Trade Inc., İstanbul 34662, Turkey
mehmet.sahin@keas.com.tr
[2] Karadeniz Technical University, Trabzon 61080, Turkey

Abstract. Wood-based panels (WBPs) are increasingly important in sustainable and circular construction due to their renewable origin, efficient use of wood residues, and recycling potential. With global WBP production reaching approximately 366 million m^3 annually, evaluating the environmental impacts associated with their production has become increasingly important. This study presents a systematic literature review of life cycle assessment research on particleboard, medium-density fiberboard (MDF), oriented strand board (OSB), and plywood using a PRISMA-based methodology and the Web of Science database. A total of 22 peer-reviewed studies published between 2015 and 2025 were comparatively analyzed in terms of system boundaries, environmental indicators, recycling approaches, and production hotspots.

The reviewed studies showed that MDF generally exhibits the highest environmental impacts, with reported carbon footprint values of approximately 500–600 kg CO_2e/m^3 due to energy-intensive fiber refining and drying processes. In contrast, OSB and plywood demonstrated comparatively lower carbon footprints ranging between 190–220 kg CO_2e/m^3 and 100–150 kg CO_2e/m^3, respectively, while particleboard typically ranged between 300–400 kg CO_2e/m^3 owing to more efficient raw material utilization and lower processing energy requirements. Adhesive production and thermal drying were consistently identified as the dominant environmental hotspots across panel types. These variations are also influenced by regional energy mixes, resin systems, and methodological assumptions.

Overall, the review highlights the importance of recycling pathways, cascading utilization, and methodological consistency in supporting circular wood-based panel production systems with lower environmental impacts.

Keywords: Wood-Based Panels · Life Cycle Assessment (LCA) · Recycling · Circular Design · Sustainable Construction

1 Introduction

The construction sector is one of the largest consumers of natural resources and contributes significantly to global greenhouse gas emissions. Current estimates indicate that, considering both operational and embodied carbon emissions, the built environment accounts for approximately 37% of global energy-related carbon emissions. While

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energy-efficient building technologies have achieved notable progress in reducing operational energy consumption, the embodied carbon associated with building materials remains a critical challenge in transitioning to sustainable construction systems [1]. Wood-based panels are increasingly recognized as environmentally advantageous alternatives to traditional construction materials such as concrete and steel. In addition to being renewable, wood products can store biogenic carbon throughout their service life, contributing to climate change mitigation strategies. The Intergovernmental Panel on Climate Change has highlighted that the use of long-lived wood products in buildings can play a significant role in reducing the carbon footprint of the built environment [2].

WBPs are engineered materials produced by combining wood particles, fibers, or veneers under heat and pressure using adhesives (Table 1). Among wood products, engineered panels-including particleboard, fiberboard (FB), oriented strand board (OSB), and plywood (PW)-are widely used in both structural and non-structural applications, such as interior components, furniture systems, flooring, roofing, and wall cladding [3].

Table 1. Classification of Wood-Based Panels [4]

Panel Type	Typical Density (kg/m^3)	Production Highlights	Typical Application
Particleboard	400–800	Pressed at moderate temperatures; adhesive dominates environmental footprint	Interior wall panels, subfloor layers, partition elements, interior finishing components
Fiberboard	400–1000	High energy use for fiber refining and drying; adhesive is a key impact contributor	Interior wall cladding, door panels, mouldings, decorative interior building components
Oriented Strand Board	600–1200	Directional pressing; resin production and drying emissions are dominant	Structural sheathing, wall and roof panels, subflooring systems
Plywood	400–800	Drying veneers, adhesive bonding; energy intensive for hot pressing	Structural panels, roof and wall sheathing, formwork panels

The global WBP industry has experienced significant growth in recent years in response to increasing demand from the construction and furniture sectors. According to Food and Agriculture Organization (FAO) data, global WBP production reached approximately 366 million m^3 per year. Table 2 presents production volumes of WBPs in the World, Europe and Türkiye between 2022–2024 [5].

Life Cycle Assessment defined by ISO 14040 and 14044, provides a standardized framework to evaluate environmental impacts of wood-based panels (WBPs) across their life cycle [6]. Circular construction principles-emphasizing resource efficiency, modular

Table 2. Global Wood-Based Panel Production

Region	Wood based panel	Unit	2022	2023	2024
World	Fiberboard	m^3	101.217.595	97.652.533	96.484.521
	Oriented strand board		38.401.234	42.373.082	46.557.582
	Particleboard		105.965.067	113.136.576	122.986.475
	Plywood		112.719.427	109.128.580	113.262.239
Europe	Fiberboard		19.417.128	17.215.094	17.772.025
	Oriented strand board		9.703.104	10.428.087	10.467.297
	Particleboard		41.947.727	41.243.714	42.389.038
	Plywood		8.424.846	8.183.085	8.610.287
Türkiye	Fiberboard		6.300.000	7.000.000	6.800.000
	Oriented strand board		75.000	75.000	75.000
	Particleboard		4.300.000	4.600.000	4.330.000
	Plywood		620.000	605.000	605.000

design, and material reuse-enhance WBPs' potential for recycling and cascading use. Environmental performance is influenced by raw material supply, adhesives, production energy, and end-of-life management, with adhesive production and thermal drying identified as major hotspots [7]. Despite growing LCA literature, studies vary in system boundaries, functional units, and regional energy contexts, often focusing on cradle-to-gate assessments of single panel types. Integration of recycling scenarios and circular strategies remains limited.

This study systematically reviews recent LCA research on particleboard, medium-density fiberboard, oriented strand board, and plywood, providing a comparative overview of environmental impacts, identifying key production hotspots, and highlighting methodological gaps.

2 Review of LCA Studies on Wood-Based Panel

A systematic literature review was conducted to evaluate recent life cycle assessment (LCA) studies on wood-based panels (WBPs). The review followed the PRISMA framework to ensure transparency and consistency in the study selection process [8]. Web of Science was selected because it provides high-quality peer-reviewed indexing and reduces duplicate records commonly encountered across multiple databases. The literature search was performed using the query:

Topic Search = ("wood-based panel*" AND "life cycle assessment")

The search was limited to English-language publications published between 2015 and 2025. Only peer-reviewed journal articles and review articles were considered. The initial search identified 38 records. After title and abstract screening, studies unrelated to

LCA methodology, non-WBP materials, and studies lacking quantitative environmental assessment were excluded. Full-text evaluation resulted in 22 studies being included in the final comparative analysis. The selected studies were analyzed in terms of system boundaries, functional units, environmental impact indicators, recycling approaches, and major environmental hotspots. Studies were included only if they reported quantitative LCA indicators and clearly defined functional units and system boundaries. Methodological differences among studies, including regional energy mixes and recycled wood utilization rates, were also comparatively evaluated. Figure 1 illustrates the PRISMA-based literature screening and study selection process applied in this review, including identification, screening, eligibility assessment, and final inclusion stages.

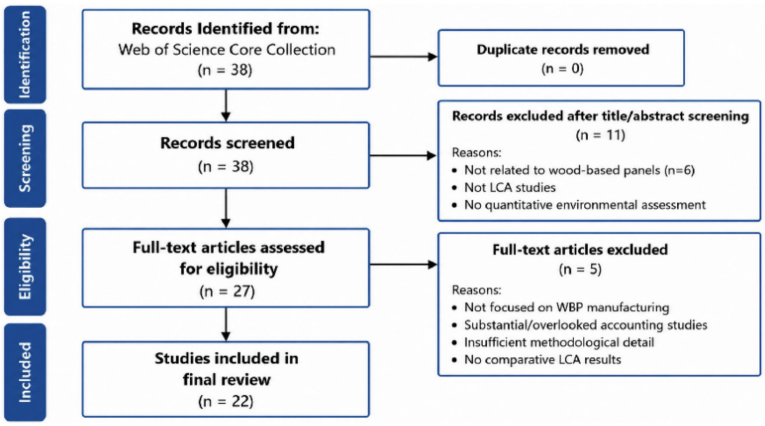


Fig. 1. PRISMA flow diagram of the literature selection process.

Figure 2 presents the comparative carbon footprint of WBPs based on literature averages, visualizing the complete life cycle: raw material extraction, panel production (resin production, drying), distribution, use phase, and end-of-life (landfill, energy recovery, recycling). Key environmental hotspots such as energy use, CO_2 emissions, and waste generation are highlighted, providing a clear view of life cycle stages for circular construction assessments [9].

LCA studies demonstrate that environmental performance varies with production technologies, energy sources, and raw materials (Table 3). PB production environmental impacts are dominated by adhesive manufacturing and drying energy. MDF production requires mechanical defibration, resin bonding, and hot pressing, with fiber refining and thermal drying as major energy inputs. The broad variation in carbon footprint values reported across studies is mainly associated with differences in regional electricity mixes, resin formulations, recycled wood content, and cradle-to-gate versus cradle-to-grave system boundaries [10, 11].

Overall, the reviewed studies consistently identify resin production and thermal drying as the dominant contributors to global warming potential across all panel types. OSB shows relatively balanced performance due to efficient strand utilization and moderate energy profiles, emerging as a promising candidate for circular applications. Plywood

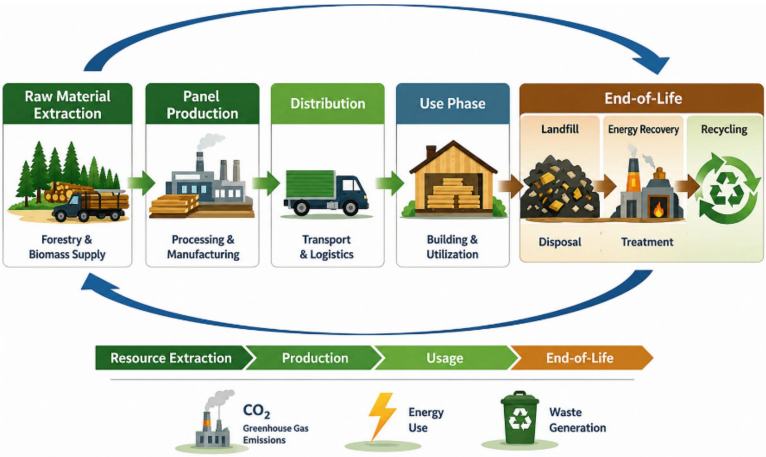


Fig. 2. Life cycle stages and major environmental hotspots of wood-based panels within circular construction systems.

Table 3. Comparative Environmental Performance of WBPs.

Panel	Energy Use (MJ/m^3)	Carbon Footprint (kg CO_2e/m^3)	Key Hotspots
PB	3.200–5.000	300–400	UF resin, pressing energy
MDF	4.000–6.500	500–600	Refining, adhesive, drying
OSB	3.500–5.500	190–220	Strand orientation, PF resin
PW	3.000–6.000	100–150	Veneer drying, adhesive

performance varies with veneer thickness, wood species, and adhesive systems, with recycling requiring mechanical separation techniques [12].

Across the reviewed studies, adhesive production and thermal drying consistently emerged as the major environmental hotspots in wood-based panel manufacturing. Environmental performance was found to vary considerably depending on resin systems, production technologies, regional energy mixes, and recycled wood utilization rates. Several studies also highlight the importance of raw material sourcing. The use of recycled wood and industrial residues can substantially reduce environmental burdens by decreasing the demand for virgin timber resources. However, the quality variability of recycled wood and the presence of contaminants such as adhesives and coatings may limit recycling rates in certain panel products.

Despite the environmental advantages of recycled wood utilization, several technical and industrial challenges remain for circular wood-based panel production. The quality variability of recycled wood, together with adhesive contamination and coating residues in post-consumer wood, may limit recycling efficiency and affect panel performance. Recycled wood is currently used more successfully in particleboard production because particle-based systems can better tolerate raw material heterogeneity

and contaminants, whereas MDF manufacturing requires higher fiber quality and more homogeneous material properties [3, 14].

3 Recycling and End-of-Life Scenarios of Wood-Based Panels

End-of-life management significantly affects the overall environmental performance of wood-based panels. Typical disposal routes include landfill, energy recovery, and mechanical recycling into secondary panel products. Mechanical recycling allows recovered wood particles or fibers to be reintroduced into new panel production, reducing the demand for virgin raw materials [13, 14].

Circular construction strategies emphasize the reuse and recovery of building materials. Modular panel systems and demountable building components allow materials to be recovered and reused at the end of a building's service life. Moreover, digital material passports can facilitate better tracking of materials and improve recycling efficiency [15]. Recent studies indicate that recycled wood recovered from demolition and renovation activities is predominantly utilized in particleboard production, where heterogeneous raw materials and residual contaminants can be more effectively tolerated compared with fiber-based panels such as MDF. Several LCA studies reviewed in this work reported that increasing recycled wood content in particleboard manufacturing can significantly reduce virgin wood demand and lower fossil-based emissions associated with raw material extraction and transportation. In contrast, MDF recycling remains more technically constrained because repeated fiber processing and adhesive contamination negatively affect fiber quality, board density uniformity, and mechanical performance. Therefore, the environmental benefits of cascading utilization in wood-based panel systems depend not only on recycling rates but also on maintaining material quality through efficient sorting, contaminant removal, and optimized secondary material flows within circular construction systems [16]. Table 4 summarizes recent LCA studies on wood-based panels and identifies the dominant environmental hotspots and system boundary approaches reported in the literature.

Comparative analysis clearly delineates environmental performance profiles for different panel types. MDF exhibits the highest carbon and energy demands due to fiber refining and high drying energy requirements. Particleboard generally performs better than MDF but has a slightly higher carbon footprint than OSB, which benefits from efficient strand use and moderate energy consumption, making it a promising candidate in the context of circular economy. Plywood's environmental performance varies depending on veneer thickness, wood types used, and adhesive systems; recycling processes require mechanical separation techniques.

Table 4. Summary of Selected LCA Studies and Reported Environmental Hotspots

Panel Type	System Boundary	Key Findings	References
WBPs	Various	Systematic review of LCA studies; most focus on cradle-to-gate	[16]
PB	Cradle-to-gate	Adhesive production and energy use account for a major part of total environmental impact	[17]
MDF & PB		PB production generally exhibits lower global warming potential than MDF due to lower energy demand and reduced fiber processing requirements.	[18]
MDF		Resin production accounts for a significant portion of total GWP	[19]
OSB & PW		OSB generally has a lower carbon footprint compared to plywood	[20]
PW		Adhesive and energy	[21]

4 Conclusions and Recommendations

The reviewed literature shows that wood-based panels (WBPs) can significantly reduce environmental impacts in construction due to their renewable origin, carbon storage potential, and compatibility with industrial production. Particleboard and OSB generally perform better environmentally than MDF and plywood because of more efficient residue use and lower energy demand.

Using recycled wood, improving production energy efficiency, and adopting renewable energy sources can further reduce carbon footprints. Circular construction strategies—such as modular panel systems enabling component reuse—extend material lifespans and reduce waste. The long-term environmental benefits of wood-based panels in circular construction systems depend not only on renewable raw material use but also on the effective integration of recycling, cascading utilization, and material recovery strategies throughout the product life cycle. Key insights include:

- **Hotspots:** Resin production and thermal drying dominate environmental impacts across panel types.
- **Panel Variability:** MDF has higher embodied carbon; OSB generally lower than MDF and plywood.
- **Recycling & Circularity:** Mechanical recycling and modular design improve lifecycle performance, though adhesive contamination remains a challenge.
- **Methodological Variation:** Differences in system boundaries, functional units, and energy mixes highlight the need for harmonized LCA frameworks.

Future research should focus on bio-based adhesives, advanced recycling, and integrated LCA approaches including cascading material use. Standardized datasets and digital material passports could enhance traceability and circularity of WBPs in sustainable construction.

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Parametric Life Cycle Cost Assessment of Timber Slabs Incorporating Circularity Strategies

Vanessa Tavares(✉), Daniel Silva, and Rita Mendonça

BUILT CoLAB, Rua do Campo Alegre 760, 4150-171 Porto, Portugal
vanessa.tavares@builtcolab.pt

Abstract. Implementing sustainability and circularity in the built environment requires design strategies that consider not only environmental but also economic performance across the entire life cycle. However, Life Cycle Cost (LCC) assessment is rarely applied as a decision-support tool, especially when externalities are included in the evaluation of timber construction. This study presents a parametric LCC assessment approach for an innovative timber-based structural system within the Universal Timber Slab (UTS) project. The methodology integrates conventional LCC—covering production, installation, and end-of-life—with a circular-economy LCC that accounts for the potential value of some circular strategies, such as reuse and recycle, as well as relevant externalities, including internalisation of environmental impacts, green labelling and green financing, faster construction times, and worker health and safety. The parametric LCC model enables streamlined evaluation of multiple design configurations, material choices, and end-of-life scenarios. It is applied to a set of UTS variations to assess the economic performance of the UTS solution. Results show that although some UTS configurations may present higher initial costs compared to conventional alternatives, circular strategies such as component reuse and material recovery can substantially reduce total life-cycle costs. The study highlights the economic viability of circular timber structural systems and provides a streamlined decision-support tool for designers, engineers, and promoters. By integrating LCC with circular-economy principles, the research supports a transition toward more resource-efficient, low-impact, and economically viable construction practices.

Keywords: Circularity · Life Cycle Costing (LCC) · Sustainability · Timber buildings · Wood construction

1 Introduction

The global construction sector faces an unprecedented challenge in reducing its environmental footprint without a substantial increase in costs, requiring a shift toward circular, sustainable, and low-carbon approaches with moderate cost solutions. A significant part of a building's life-cycle environmental burdens (impacts and costs) is due to material production and construction; therefore, material choice is central to carbon reduction

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and cost control [1]. Complementary to Life Cycle Assessment (LCA), which focuses on the environmental impacts, Life Cycle Costing (LCC) is a methodological approach that assesses the total costs incurred throughout the entire life cycle of an asset, including investment (e.g., acquisition of materials, machinery, and land), construction, operation, maintenance, replacement, and end-of-life. Unlike upfront cost comparisons, LCC captures shifts between life-cycle phases, supporting more informed long-term decisions [2]. Alternatively, low-impact materials should be analysed not only in terms of emissions but also in terms of costs.

Timber, as a renewable bio-based resource, has lower embodied impacts than steel and concrete [3]. Mass timber systems, including cross-laminated timber (CLT) and glued laminated timber (glulam), have been widely evaluated for their environmental performance in construction, but their economic performance remains less clearly defined. Available studies suggest that wood-based solutions generally involve higher initial material and construction costs than conventional reinforced concrete or steel systems [3]. For instance, combined costs of raw material extraction, transport, and construction for mass timber can reach 8.39 €/m^2, compared to 5.39 €/m^2 for reinforced concrete [4]. In a 12-storey mixed-use building in North America, mass timber had 26% higher initial construction costs when compared to concrete; and 10% higher total LC cost [3]. At the material level, when comparing six structural systems for a three-storey townhouse, CLT was found to have the highest cost (~385 €/m^2), exceeding lightweight timber, steel, aircrete, brick, and reinforced concrete [5]. Furthermore, operational and maintenance costs may also be higher for mass timber buildings, with increases of 13%–16% relative to reinforced concrete attributed to more frequent interior finish replacement and termite protection requirements [6].

Despite these higher costs, potential economic trade-offs have been identified. Offsite prefabrication enables accelerated construction schedules and reduces on-site labour, equipment use, and overhead requirements, which can partially offset higher material costs [7]. In this context, cost estimates indicate that CLT buildings may achieve approximately 18% savings in costs related to labour, transport, machinery, and overhead when compared to reinforced concrete buildings [6], contributing to lower the overall costs, with 0.9–1.3% lower costs compared with reinforced concrete. Some LCC studies indicate that mass timber buildings often remain more costly than conventional alternatives [3, 4], whereas others report lower construction-related costs for CLT [6]. Such variation in findings can be partly explained by the sensitivity of LCC outcomes to contextual factors, including regional timber availability, transport distances, and the maturity of local supply chains [8].

Most LCC studies on mass timber follow conventional approaches with two limitations: a narrow boundary that excludes environmental and social externalities, and a linear cradle-to-grave life cycle that overlooks the economic value of circular strategies such as reuse, recycling, and life extension, especially relevant for timber systems with high residual value [9]. To date, existing LCC studies have not adopted a fully integrated framework encompassing environmental, social, and economic dimensions. In particular, no studies have applied a circular and environmental Life Cycle Cost Assessment (eLCC) approach while explicitly accounting for externalities. This constitutes a

significant research gap, as eLCC better captures long-term economic performance and supports sustainability-oriented decision-making.

To address this gap, the present study focuses on glulam-based slab and aims to develop an eLCC methodology that integrates environmental, social, and economic dimensions, providing a more holistic assessment of long-term performance and sustainability-oriented decision-making.

2 Methodology

2.1 Goal and Scope

This study developed a cradle-to-cradle LCC tool to assess the costs of an innovative slab developed within the UTS project [10], with the patent WO2025082958A1 [11]. The analysis focuses on the bay as the basic element that is repeated to build up the slab. The conventional LCC approach was extended to include environmental externalities and additional circular strategies, forming an expanded eLCC framework. The functional unit is defined as the production of 1 m^2 of a slab bay used as a floor element in a multi-story timber building, with a reference service life (RSL) of 60 years.

This preliminary slab adopts a timber–concrete hybrid system, where timber resists tensile stresses at the bottom and concrete carries compressive stresses at the top. It consists of 18 triangular bays, with 21.9 m^2, arranged in pairs over a 5.4 × 8.1 m span (Fig. 1). Each bay is divided into three segments, with additional cantilevered segments connecting the bays to the slab perimeter. In terms of fabrication, this study considers the mill-nailing per group approach, where milling and nailing occur during group assembly, followed by pressing for consolidation. The results presented are work in progress from the ongoing study [12].

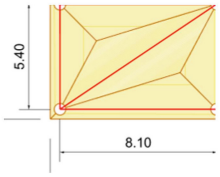


Fig. 1: UTS Building System: one bay.

2.2 Parametric LCC System and eLCC System Definition

The LCC process includes the foreground that covers the production stage, focusing on bay manufacturing costs and the background comprises processes outside the manufacturer's control, beyond the gate. The LCC represents the UTS production system, where circular strategies are applied conventionally, limited to recycling and energy recovery of timber (R8 and R9 in the circularity hierarchy). Four end-of-life (EoL) scenarios are considered: waste management (waste delivered to a facility, Sc0), 100% recycling of

timber into pellets (Sc1), 100% incineration with energy recovery (Sc2), and a 30% recycling / 70% incineration with energy recovery scenario (Sc3).

The eLCC approach used in this study incorporates externalities that are typically not captured, distinguishing it from whole LCC. These were first identified by the project consortium across the three pillars of sustainability and then selected based on their relevance, added value and data availability. System boundaries are also expanded beyond direct financial costs to capture impacts linked to circular strategies across the life cycle. Figure 2 presents the UTS eLCC process flowchart, which includes a redesign phase (R1 – rethink, R2 – reduce) embedded in the UTS project. At the EoL, the timber from the bay can be reused (R3), recycled (R8) within a closed-loop system to produce recycled timber, or sent to energy recovery (R9) if reuse or recycling is not feasible. By incorporating these alternatives, the system boundaries are expanded to support a more circular model across the product life cycle.

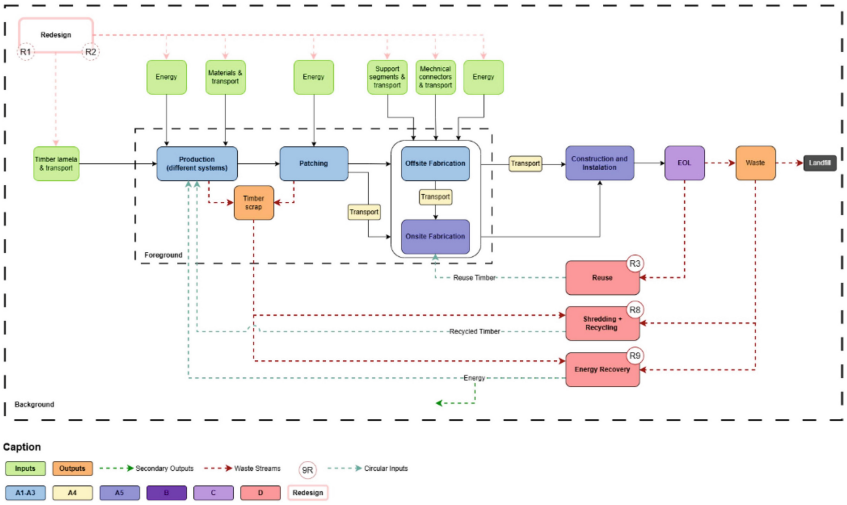


Fig. 2: UTS flowchart: the eLCC of the bay.

Table 1 outlines the various circularity scenarios evaluated within the eLCC framework, detailing the sensitivity analysis of the different percentages of reused, recycled and new timber (at production stage) and reusable, recyclable and landfilled (at EoL). The baseline scenario is based on the EU Annex guidelines for the EoL treatment of timber, assuming a 30% recycling rate and a 70% incineration rate [13].

Environmental, economic, and social externalities were assessed for the eLCC model. Five strategies were selected: i) circular strategies, ii) internalization of environmental impacts, iii) green labels and financing, iv) faster construction times, and v) workers' health and safety. Circular strategies capture the economic implications of life-cycle actions such as reuse and recycling with baseline scenario representing current feasibility and future scenarios to explore future technical limits. Internalisation of environmental impacts reflects the monetised cost of greenhouse gas emissions (GHG), calculated by multiplying LCA-derived global warming potentials (from the UTS LCA team) by

Table 1. Circularity alternatives considered for the eLCC.

Circularity Alternatives	New Timber	Recycled Timber	Reused Timber	Recyclable Timber	Reusable Timber	Incineration
Baseline (A0)	**100%**	**0%**	**0%**	**30%**	**0%**	**70%**
Max. Recycled (A1)	**70%**	30%	0%	Same as baseline		
Max. Reused (A2)	10%	0%	**90%**			
Reused (A3)	**50%**	0%	**50%**			
Max. Recyclable (A4)	Same as baseline			**70%**	0%	30%
Max. Reusable (A5)				30%	**90%**	10%
Recyclable / Reusable (A6)				**40%**	**40%**	20%

the European Union Emissions Trading System (EU ETS) carbon permit price. Green label and green financing capture the financial advantages associated with achieving green building certification, including access to lower interest rates. The values for the green label costs were retrieved from the BREEAM website, and financing assumptions were based on European Central Bank data and Leutner et al. (2024) [14]. Faster construction accounts for labour and time savings enabled by modular prefabricated timber systems, assuming traditional construction requires 40% more time [15]. Worker health and safety reflect economic benefits from reduced accident risks and improved working conditions in controlled modular environments. These benefits are quantified by aggregating direct healthcare, indirect productivity and intangible health-related quality of life costs, weighted against the annual frequency of accidents [16].

2.3 Life Cycle Inventory (LCI)

The LCI analysis involves the collection and calculation of inventory data to quantify the input and output flows of the assessed systems. Inventory data for materials and the production stage were obtained directly from the UTS project team at the University of Stuttgart, while data for the remaining life cycle phases were supplemented using literature sources and established databases. Production consists largely of concrete (49%), timber (30%), hardwood nails (11%), and the floor buildup (10%), along with minor inputs and energy/labour. Transport includes 300 km to site (A4) and 50–100 km to end-of-life destinations (C stages), with waste mainly composed of concrete (49%) and

timber (41%). Cost data were compiled from market analyses and construction-specific sources, including Gerador de Preços, Eurostat, CNR, and online retail suppliers.

3 Results and Discussion

The A1–A3 production stages dominate the costs with 524 €/m^2 followed by EoL phase, especially in the Sc0 scenario, where it accounts for 162 €/m^2. The LCC results show differences across the four analysed scenarios (Fig. 3). The Sc0 scenario has the highest total cost at 721 €/m^2, while Sc1 is the lowest at 555 €/m^2. Intermediate costs are 583 €/m^2 for Sc2 and 574 €/m^2 for the Sc3 scenario. These variations are mainly due to economic offsets at (stage C) or beyond EoL (stage D): Sc1 reduces about 92 €/m^2 of cost from material recycling. Sc2 reduces costs from energy recovery through incineration (46 €/m^2), whereas Sc3 relates to a combination of recycling and energy recovery through incineration (59 €/m^2). Within the production stage (A1-A3), timber has the highest cost, accounting for over 48% of costs, followed by the floor buildup with 32%.

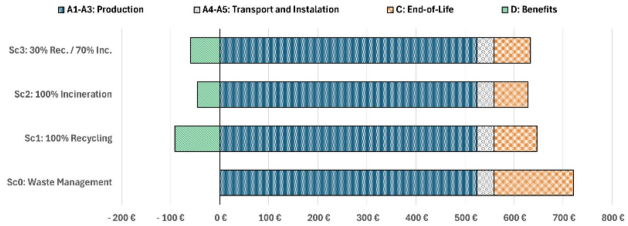


Fig. 3: LCC results (€/m^2) for bay production.

Within the eLCC analysis, the effect of varying the share of reused/recycled timber at the product stage and reusable/recyclable timber at EoL was assessed (Table 1). As shown in Fig. 4, the "Max. Reused" scenario achieves the lowest eLCC (352 €/m^2), representing a 39% reduction compared to the baseline. The "Reuse" scenario (50% reused bays) also shows a significant 24% decrease, while the "Max. Recycled" scenario achieves a 15% reduction.

EoL circular scenarios provide more moderate improvements: "Max. Reusable" reduces costs by 10%, "Recyclable/Reusable" by 9%, and "Max. Recyclable" by 8%. Overall, reuse strategies deliver the greatest economic advantage, with recycling and mixed EoL options offering smaller but still relevant savings. These results demonstrate that reuse strategies generally provide the greatest eco-nomic advantage, while recycling and mixed EoL strategies offer moderate, yet relevant, cost savings.

Figure 5 shows the contribution of each externality considered in this study. Results indicate that, excluding circular strategies, remaining externalities largely offset each other. Internalising environmental impacts increases costs by 4%, while the green label and reduced construction time decrease costs by 3% and 0.3%, respectively. The effect of worker health and safety is negligible at this scale.

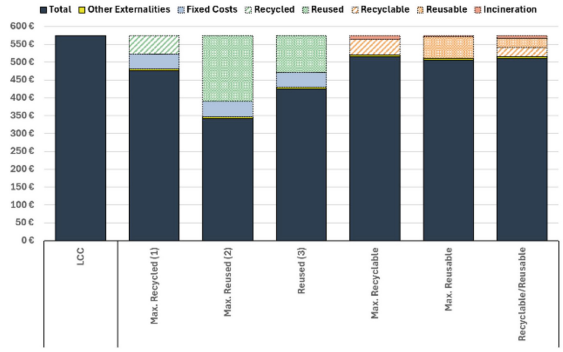


Fig. 4. eLCC results for the different circular scenarios.

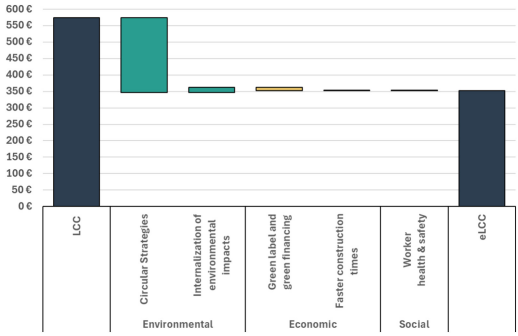


Fig. 5: Breakdown of the eLCC externality costs for the 'Max. Reused' scenario.

4 Conclusion

This study evaluated the life cycle costs (LCC) and environmental and circular life cycle costs (eLCC) of a timber bay under different circular scenarios. Results show that production stages (A1–A3), particularly timber, dominate total life cycle costs. The most favourable outcome was Sc1 (100% Recycling), while Sc0 (Waste Management) was the least favourable, mainly due to differences in end-of-life resource recovery.

The eLCC results highlight the economic benefits of circular strategies, especially reuse, which can reduce total costs by up to 47%. Recycling and other end-of-life options provide more moderate savings, while environmental, economic, and social externalities have a limited overall effect.

Overall, the results demonstrate that applying circular strategies to timber, particularly reuse, can reduce life cycle costs and help offset upfront costs. Extending these strategies to other construction materials and systems could further enhance the economic performance of the UTS solution and increase its market acceptability.

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BIM-Based Tool for Carbon Emission Calculation in Construction Design Workflow

Leonardo da Silveira Pirillo Inojosa(✉) and Thiago Torres Ribeiro

Universidade de Brasília, Brasília, DF 70910-900, Brazil
leinojosa@unb.br

Abstract. The escalating global concern for environmental sustainability has placed significant pressure on the construction industry, a major contributor to carbon emissions, to adopt more effective methodologies for assessing and mitigating its ecological footprint. This issue has led to the development of advanced digital tools, particularly those integrated with Building Information Modeling. BIM-based methodologies offer a framework for integrating sustainable practices throughout the project lifecycle, from initial design to facility management. This study presents a method for calculating carbon emissions from BIM models and develops a tool to estimate emissions during the project design phase. This methodology utilizes a comprehensive database that details the environmental performance of key construction materials, derived from life cycle assessment (LCA) principles. The tool leverages Dynamo to extract model information from Revit and export it to an Excel spreadsheet for detailed carbon emissions calculations, enabling precise, integrated environmental analysis and decision-making. Additionally, this study highlights the necessity of enhancing designers' awareness concerning the environmental impacts of construction materials and structural configurations. The integration of such tools directly into the design workflow facilitates proactive environmental optimization, allowing for informed material selection and design modifications to reduce embodied carbon before construction.

Keywords: BIM · Carbon emissions · Design Workflow · Sustainability · Life cycle assessment

1 Introduction

The civil construction industry constitutes one of the main drivers of carbon dioxide emissions globally [1]. In light of the climate urgency, it becomes imperative for the sector to adopt effective methodologies to assess and mitigate its ecological footprint. The development of advanced digital tools, particularly those integrated with Building Information Modeling, emerges as a technological response to this demand [2], enabling the automation of material inventories and the dynamic calculation of embodied emissions during the initial design stages [3, 4].

BIM-based methodologies provide a robust framework for integrating sustainable practices throughout the life cycle of the built object. In the project context, the ability

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to anticipate the environmental performance of materials and structural configurations is fundamental for reducing embodied carbon [5]. This study presents a method for calculating emissions from BIM models and details the development of a tool to estimate emissions in the design phase.

2 Theoretical Framework

2.1 BIM and Sustainability in the Construction Industry

The application of BIM transcends geometric representation, establishing itself as a holistic process of information management. In the context of sustainability, the focus lies on minimizing resource consumption. The integration of Life Cycle Assessment into the BIM workflow enables integrated environmental analysis, facilitating data-driven decision-making based on precise environmental performance data, allowing designers to compare material alternatives and quickly identify carbon impacts before the execution phase [1]. This digital interoperability minimizes the need for manual data entry, mitigating errors and optimizing the efficiency of the environmental assessment process [6].

2.2 Life Cycle Assessment and Embodied Carbon

LCA is a technique that allows measuring the potential impacts of a system throughout its existence [1]. According to ISO 14040, LCA is structured into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [7]. In construction, this methodology enables focusing on embodied carbon, which refers to greenhouse gas emissions from extraction to assembly [1].

This research focuses on stages A1 to A3 (cradle-to-gate), comprising raw material extraction, transportation, and manufacturing, aligning with the "cradle-to-gate" life cycle [8]. The choice is justified by the reliability of data in Life Cycle Inventories and the direct influence of the designer on these phases. Focusing on these stages is essential as they represent the bulk of the embodied carbon of construction materials, where the designer has the most significant influence.

2.3 BIM-LCA Integration in the Project Workflow

The integration addresses the challenge of data fragmentation. According to Xue et al. [9], the main advantage is to perform iterative analyses. Automated extraction through parametric models mitigates the uncertainties of manual surveys, ensuring that the Global Warming Potential (GWP) calculation aligns with real-time decisions. The use of Dynamo fills the interoperability gap between modeling software and environmental databases [1].

Thus, the parameterization of BIM objects enables life cycle inventories to be updated dynamically, enhancing the selection of materials with a reduced carbon footprint from the early conceptual phases. This approach promotes circularity by allowing the quantitative evaluation of modular construction solutions and the precise analysis of materials'

environmental impacts, consolidating decision-making based on performance indicators throughout the entire building life cycle [10].

While established commercial tools such as Tally and One Click LCA offer robust Life Cycle Assessment (LCA) plugins within the BIM environment, their deployment faces technical and economic barriers in developing economies. Commercial plugins often rely on international databases (such as Ecoinvent or GaBi) that do not faithfully represent the Brazilian industrial matrix or local electricity grid emissions. Furthermore, high licensing costs limit their widespread adoption in public projects.

The development of a custom Dynamo-Excel workflow addresses this gap by directly mapping native Revit parameters to national cost and environmental indices like SINAPI. This open-access framework democratizes carbon accounting in the design workflow, providing a scientifically justified alternative tailored to local regulatory contexts without financial overhead.

2.4 Structural Protagonism in Construction

The evolution of construction over time is intrinsically linked to the materials and technologies adopted for structural systems. The protagonism of the structure in defining architecture reflects an integration in which the structural system defines the architectural form itself. However, aesthetics based on large spans or bold plastic forms entail a significant environmental impact due to high material consumption, such as cement and steel [11].

Given that the structure is often the subsystem with the largest material volume, optimizing it offers the greatest leverage for decarbonization. Analysis of structures reveals that technological control and precision in specification, now enhanced by BIM, allow for accurate quantification of embodied carbon impact. Consequently, parametric optimization of these structural elements becomes vital for reducing embodied energy, enabling designers to evaluate trade-offs between spatial efficiency and the environmental load of components [12].

3 Methodology

The research followed a methodological design divided into four main stages: literature review; collection of carbon emission coefficients; tool development; and validation through a case study.

For data collection, the Inventory of Carbon and Energy (Inventário de Carbono e Energia - ICE) and the National System for Research on Construction Costs and Indices (Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil - SINAPI) were used as a basis, focusing on embodied carbon (“cradle-to-gate”).

3.1 Workflow and BIM-Dynamo Integration

The tool was designed to operate integrally within the design workflow, using Autodesk Revit as the parametric modeling software and Dynamo as the automation engine (Fig. 1).

The process begins with the correct categorization of elements in the BIM model, ensuring that the volume and material parameters are correctly completed.

The script developed in Dynamo operates on three fronts:

- Category Selection: Filters the construction elements that compose the structure and enclosure.
- Parameter Extraction: Collects volume (m^3) and area (m^2) data directly from Revit families.
- Interoperability: Exports this data to an external Excel spreadsheet, where carbon emission coefficients are applied automatically.

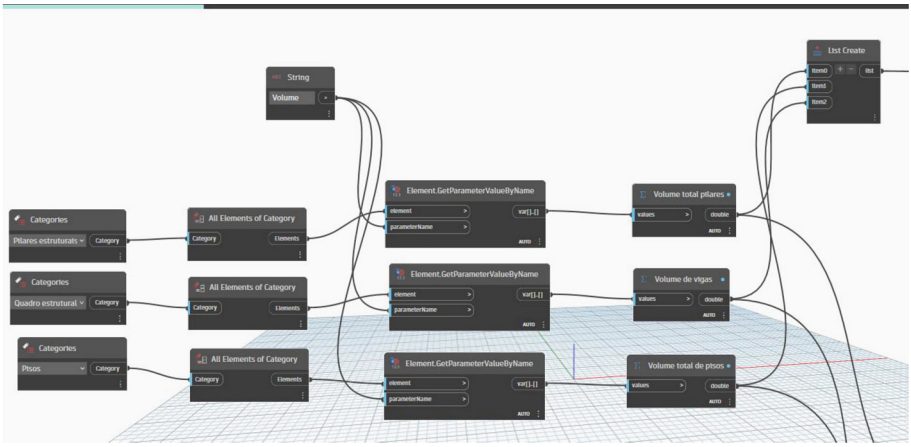


Fig. 1. Visual programming routine in Dynamo environment for extracting quantities from Revit categories. Source: Adapted from Ribeiro, 2024 [1].

3.2 Carbon Calculation Criteria

The calculation is based on the quantification of embodied carbon, specifically in the "Cradle-to-Gate" stage, which comprises raw material extraction, transportation, and manufacturing [13]. The base formula applied in the tool is (1):

$$E_{total} = \sum (V_i \times \rho_i \times FE_i) \tag{1}$$

Where:

- V_i is the volume of material extracted from the BIM model.
- ρ_i is the density of the material.
- FE_i is the emission factor (CO_2 eq/kg) obtained from inventories such as ICE and adapted to the Brazilian context via SINAPI.

3.3 Case Study

As a methodological validation tool, the study utilized the standard project of the FNDE Creche Pré-Escola Tipo 1. This project holds special importance due to its widespread replication across the national territory [1], conferring high potential social and environmental impact to the study. The BIM model of the daycare (Fig. 2) enabled testing the tool on a complex geometry integrating various constructive subsystems.

In this application, different material scenarios were compared to assess the variation in total carbon dioxide equivalent ($CO_2\ eq$) emissions.

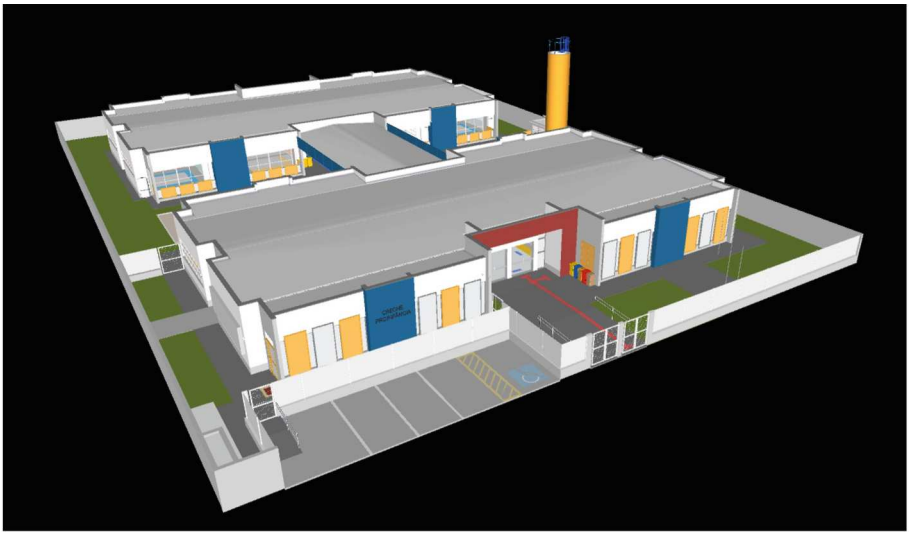


Fig. 2. Three-dimensional representation of the BIM model used for testing the tool. Source: Authors.

4 Results and Discussions

4.1 Analysis of Emissions in Creche Type 1

The 3D visualization facilitated the identification of oversized elements that impacted the carbon footprint. The application of the tool to the FNDE Creche model revealed that reinforced concrete structural systems are the main contributors to the building's carbon footprint. This diagnosis underscores the need to explore material alternatives with lower emission factors, as suggested by frameworks that automate the comparison of alternatives based on inventory data.

- **Critical Points Identification.** Automated extraction enabled the identification that in standardized projects, careful material specification can significantly reduce the

global impact without altering the building's functionality. Additionally, the interoperability between the modeling environment and calculation spreadsheets allowed variations in emission coefficients to be reflected in real time, validating the effectiveness of automation in mitigating human errors and ensuring inventory precision.

- **Subsystems Comparison.** The comparison of various subsystems simultaneously identified the structure as the largest share of embodied carbon in the project, reinforcing the need for structural optimization in large-scale public sector projects. Parallel to the data demonstrate that the strategic replacement of high-impact components with circular alternatives or lower footprint options can substantially reduce total emissions, corroborating the technical feasibility of integrating sustainability metrics from the initial modeling phases.

4.2 Proactive Decision Making

The tool enabled the simulation of different material scenarios for the daycare building. By altering the concrete class or enclosure type in the BIM model, the impact on total CO_2 *eq* emissions was recalculated instantly (Fig. 2). This demonstrates that transparency of environmental data in the design workflow increases the designer's awareness and facilitates the selection of lower-impact materials (Fig. 3).

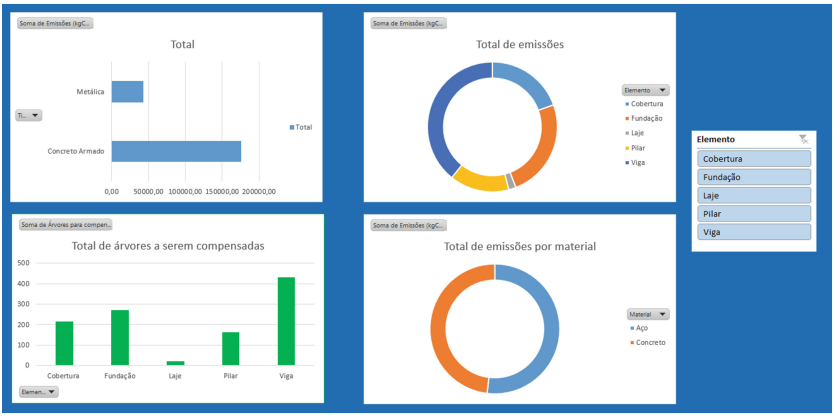


Fig. 3. Graph of emission distribution by material in the Structural Model for FNDE Daycare Building. Source: Ribeiro, 2024 [1]

4.3 Quantitative Baseline Results

The automated extraction of the FNDE Creche Tipo 1 BIM model yielded a total material volume that translated into an overall embodied carbon footprint of approximately 342.5 tCO2eq for the structure and envelope components (Stages A1–A3). The reinforced concrete structural system (beams, columns, and slabs) alone accounted for 68.2% of the total emissions, confirming the structural protagonism discussed by Inojosa (2019).

4.4 Material Scenario Comparison

To validate the tool's utility in proactive decision-making, two structural scenarios were simulated:

- **Scenario A (Baseline):** Standard structural concrete (CP II concrete blend) resulted in 233.5 tCO2eq for the structural frame.
- **Scenario B (Eco-optimized):** Replacing standard concrete with a pozzolanic ash-blend concrete (CP IV) reduced the structural embodied carbon to 191.4 tCO2eq, representing an instantaneous 18% reduction in the structural footprint.

This real-time feedback loop inside the Excel sheet allows designers to quantify environmental optimizations before any material procurement begins.

4.5 Data and Interoperability Challenges

The effectiveness of the tool is linked to the maturity of the information in the model, facing the following technical challenges:

- **Level of Development:** The accuracy of calculations depends on an adequate LOD (ideally >300), as simplified models omit essential components, resulting in underestimates of embodied carbon.
- **Parametric Integrity:** Failures in filling "Material" and "Volume" parameters in Revit make automation via Dynamo unfeasible, requiring rigor in modeling [14].
- **Inventories and Local Reality:** Dependence on external databases imposes the challenge of constant updating and adaptation of international coefficients to the Brazilian energy and industrial matrix [1].
- **Interoperability:** Barriers persist in data transition between BIM and calculation environments, especially for non-standardized systems.

Overcoming such limitations is fundamental so that automated analysis is not restricted to post-design stages, allowing sustainability metrics to guide design from its conceptual phases.

5 Conclusion

The present study demonstrated the technical feasibility of integrating visual programming tools into the BIM workflow for carbon emissions management. The developed tool proved effective in automating quantity takeoffs, mitigating errors inherent to manual processes, and allowing sustainability to consolidate as an iterative design parameter essential for managing the carbon footprint of the AEC industry in a technically rigorous manner.

The FNDE Creche Pré-Escola Tipo 1 case study validated the tool in a replicable and socially relevant context, highlighting the significant environmental impact of structural systems. The use of BIM-LCA to optimize material consumption is crucial for decarbonizing the sector. However, the study's focus on stages A1–A3 (Cradle-to-Gate) limits

the application of circular economy principles. Future iterations must incorporate structural disassembly, materials reuse, and end-of-life processes (C1–C4) to fully capture material value retention in a circular built environment.

The precision of environmental analysis relies on the model's Level of Development and the integrity of parametric data. Successful implementation requires both technological mastery and clear guidelines in BIM Execution Plans. Future work should expand the database to include maintenance and end-of-life phases and integrate with cost databases for a balance between ecological efficiency and financial viability. Ultimately, democratizing environmental analysis tools in project workflows can transform the construction industry into a more advanced and environmentally responsible sector.

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From Operational to Embodied Emissions: Insights into the LCA of Key Building Systems

Anna Dalla Valle(✉), Fabrizio Leonforte, Andrea Campioli, Monica Lavagna, Claudio Del Pero, and Niccolò Aste

Department of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, Milan, Italy
anna.dalla@polimi.it

Abstract. After years in which operational emissions dominated the international debate on building sector, embodied emissions are now receiving increasing attention, proved by policy requirements that extend the assessment to construction materials and technical building systems. Nevertheless, building systems are often overlooked or modelled using database values that do not accurately reflect their real physical composition. Focusing on key systems relevant to building decarbonization, the paper aims to evaluate the material intensity and associated environmental impacts, pointing out the complexities underlying the LCA modelling of three technical systems – Heat Pump, Water Loop Fan Coil, and Multi Converter – developed in RE-SKIN Horizon project. The intensity of the embedded materials/components has been defined through close collaboration with manufacturers to obtain primary inventory data, collected by a process that balances simplification with an adequate level of detail. Environmental impacts have been assessed in compliance with EN 15804 + A2, focusing on GWP as key indicator. The results provide a highly granular understanding of the resources invested into building systems and, especially if they emerge as hotspots, to be handled over the entire life cycle. This is crucial for improving product-level environmental performance and, when scaled up, for supporting building-level characterization.

Keywords: Life Cycle Assessment · Building System · Inventory · Impacts

1 Technical Building Systems at the Spotlights

The shift from operational to embodied emissions in the building sector is now imperative, consolidated by recent policy developments, notably the recast of the Energy Performance of Buildings Directive [1], which extends the scope of assessment to the whole life cycle greenhouse gas emissions. If operational emissions have dominated for a long time, in recent years embodied emissions have been increasingly deemed 'critical', particularly in highly efficient or nearly zero-emission buildings, in which operational impacts are progressively reduced. In this respect, several Life Cycle Assessment (LCA) studies conducted at building level highlight the significant contribution of embodied impacts to total life cycle impacts, specifically underlining the importance of technical

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and electrical equipment [2–4]. Beside construction products, the inclusion of these systems in building assessment is essential, even if they are still often omitted in practice or covered superficially for a variety of reasons (mainly lack of environmental data). Neglecting building systems, or modelling them only partially, means to overemphasize the saving in term of operational emissions, ignoring the material intensity and upstream impacts associated with the technologies used to achieve such savings [5, 6]. The omission or partial accounting of the embodied emissions from building systems may lead to incomplete and potentially misleading LCA evaluation.

In this context, the present paper provides insights into material intensity and environmental impacts of key building systems currently used for building decarbonization: Heat Pump, Water Loop Fan Coil, and Multi Converter (details in paragraphs below). The study has been developed within the project RE-SKIN "Renewable and Environmental-Sustainable Kit for building Integration" [7], funded in the framework of the Horizon programme, aimed at assessing the related life cycle impacts. Moving beyond a preliminary assessment largely based on assumptions, the work relies on detailed primary data inventories, subjected to process of simplification to achieve a high level of modelling granularity while preserving feasibility. The resulting analysis contributes to more accurate measurement of product-level environmental performance within the RE-SKIN toolkit, subsequently implemented and validated in real case-study buildings.

2 RE-SKIN Toolkit

RE-SKIN is an integrated multifunctional system for the energy retrofit of existing buildings, addressing both the envelope (roof and façade) and HVAC system [8], the latter being the focus of this study. The roof is renovated through a building-integrated hybrid photovoltaic-thermal (BIPVT) system that generates electricity and heat while providing thermal and acoustic insulation. The air heated by the hybrid roof supports heating and domestic hot water via a solar-assisted air-to-water Heat Pump able to provide 18kWp. Furthermore, as the system operates in direct current (DC), the electricity produced by BIPVT directly supplies the Heat Pump without AC conversion, thereby improving overall system efficiency. The DC Heat Pump is also connected to decentralized DC water loop heat pumps installed in each room, enabling both heating and cooling via the building hydronic network. Such components integrate a DC compressor to increase the thermal power (about 1.5 kW each) coming from the centralized DC heat pump, according to the energy demand of each room. This allows to minimize heat losses on the existing distributions pipes and to avoid condensation in cooling mode.

In addition, an energy storage system composed by repurposed electric vehicles batteries is also included, to store PV electricity. All AC/DC power fluxes, including grid interfacing, are managed by a Multi Converter that allows the interconnection of multiple DC generators, DC loads and energy storages. It avoids the DC/AC conversion from the PV modules and thus the presence of a plant-sized PV inverter, regulating the voltage and/or current, without other power modulation equipment. Moreover, it allows a bi-directional power flow with the AC grid whenever the generated/stored DC energy is insufficient, or when excess PV electricity cannot be stored locally.

3 Ways to Approach Detailed System-Specific Inventories

Developing a detailed life cycle inventory for technical building systems is particularly demanding, calling for iterative collection process as experienced with RE-SKIN partners. Many sub-components could be not standard products, with limited pre-existing information. Furthermore, given the high number of sub-components and the supply chain articulation, information is always fragmented, non-digitized and dispersed across suppliers, making data collection complex and time-consuming. From the manufacturer point of view, compiling a detailed inventory typically entails a manual breakdown of the system, that requires a considerable internal coordination across technical, procurement and assembly areas. From the LCA analyst point of view, an additional effort is demanded to keep operators informed about the needed information and clarify their relevance for the environmental modelling, translating LCA requirements into practical instructions for manufacturers and establishing priorities for the data collection. This mutual learning process is fundamental for achieving appropriate balance between simplification and modelling granularity.

Depending on the technological and component complexity of the systems under investigation as well as the state of awareness and resources monitoring within the company, in terms of inflows and outflows, two methodological pathways can be identified. They derive from industrial collaboration, and they are replicable to approach a detailed inventory for building systems.

The first way – here applied to Heat Pump and Water Loop Fan Coil – consists of the single-item breakdown of the system. This method requires the identification of each individual sub-component constituting the product and its systematic characterization in terms of material type, quantity, unit weight and total mass. Additional process-related elements, such as auxiliary materials, refrigerant and manufacturing energy consumption, are integrated. In this way, although some simplification in relation to material composition, a high level of granularity is ensured, allowing a detailed identification of hotspots, nonetheless substantiated by considerable effort in terms of data collection. Following this approach, the collected data are related to: 63 items for the main unit and 65 items for the evaporator, complemented by refrigerant and manufacturing energy consumption, for the Heat Pump; 31 items, complemented by refrigerant, for the Water Loop Fan Coil.

The second way – here adopted for Multi Converter – is based on the aggregated-item strategy, needed to face highly complex electronic systems tailor-made as in this case for RE-SKIN toolkit. Instead of characterizing each item individually, sub-components are grouped into functional clusters. These clusters are then associated with representative material categories, quantified based on their overall weight and, whenever possible, to the technical arrangement (e.g. number of units per module and number of modules per system). Further refinements of the inventory are encouraged for the most material-intensity clusters. In this way, feasibility and representativeness are in a sense ‘offset’, remaining balanced to enable complex multi-component systems to be modelled without excessive simplification and by avoiding disproportionate analytical efforts. In particular, the inventory has been structured considering, for the Multi Converter, around 4500 items aggregated into a matrix of 7 aggregated-item groups and 6 main material categories.

Both methodological pathways aim to achieve enough level of detail to capture the material intensity and environmental hotspots of the system, ensuring practical applicability in relation to the manufacturer maturity.

4 LCA Modelling of Building Systems

In the present study, the LCA of key building systems – namely Heat Pump, Water Loop Fan Coil and Multi Converter – specifically designed within the Horizon project RE-SKIN, has been carried out in compliance with EN 15804 + A2 [9], consistently with Level(s) framework [10] requirements. The LCA modelling considers one complete system (1 p) and focuses primarily on Global Warming Potential (GWP), following a cradle-to-gate boundary (A1-A3 modules), and it has been performed using SimaPro 9.6 software, with background data sourced from Ecoinvent 3.10 database.

Depending on the inventory details available from the manufacturers, the following approaches have been implemented during the systems modelling:

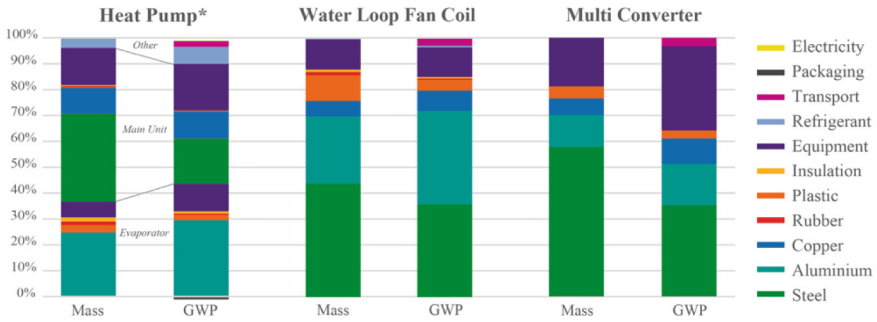
- for mono-material items (e.g. support plate), the environmental profile was directly linked to a specific representative material dataset (e.g. *'Aluminium alloy, AlMg3'*);
- for double/triple-material items (e.g. pipe insulation), the modelling focused on the most relevant constituent (e.g. '*Polyurethane, flexible foam'*), because the missing data about materials share made the allocation to individual materials not feasible, forcing the cut-off of minor constituents (e.g. acrylate adhesive);
- for multi-material items (e.g. inverter and control units), the modelling was preferred where available at product-level (not material), by selecting representative background dataset for functionally equivalent products (e.g. *'Inverter'* and *'Electronics, for control units'*). This approach allows to depict highly complex assemblies, composed of several sub-components and materials, avoiding impractical level of disaggregation.

With regard to transport, the absence of information on the upstream supply chain required the adoption of assumptions. For both material-level and product-level, *'market for'* datasets have been selected in order to account, although in a simplified manner, the geographical fragmentation and foreign sourcing of sub-components, often produced outside the European Union. For the final stage of the supply chain, namely from the sub-component supplier (e.g. valve producer) to the building system assembler (e.g. Heat Pump manufacturer), a standard transport distance of 1000 km by lorry has been taken. Packaging materials, both for incoming items and outgoing products, and manufacturing waste were excluded from the system boundary due to lack of data.

5 Combined Results of Material Intensity and GWP Impacts

The LCA results are presented by explicitly linking material intensity (expressed in kg of materials per complete system) with the associated A1-A3 environmental impacts, taking GWP as key indicator (expressed in $kgCO_2e$ per complete system). Note that despite the effort in data collection to ensure granularity, the detailed inventories developed for each system and the resulting impacts were re-aggregated into main material areas to

return results as percentage (Fig. 1). This clustering step was necessary to improve visual clarity and consistency graphics, especially in systems modelled through fully disaggregated single-item breakdown, in which the large number of individual sub-components would otherwise hinder readability. The matching between material mass distribution and GWP contribution allows a direct understanding of how material intensity translates into embodied emissions.



* Heat Pump materials are aggregated but reported separately for main unit and evaporator.

Fig. 1. Percentage distribution of material intensity and GWP impacts for the 3 building systems.

5.1 Heat Pump

The total GWP (A1-A3) of the Heat Pump, referred to one complete system, amounts to 3.36E+03 kgCO_2e. The cumulated mass of the system is 366 kg, composed of 218 kg for the main unit, 135 kg for the evaporator and 13 kg of refrigerant (excluding the wooden pallet used for packaging). The GWP hotspot analysis confirms that the main unit is the largest contributor to total embodied emissions (47%), closely followed by the evaporator (45%), while the remaining elements – refrigerant, packaging, transport, energy, grouped under *'Other'* – account for a minor share (8%).

Within a more detailed breakdown of the main unit, complex equipment represents the primary hotspot (52.6 kg generate 39% GWP impacts of main unit only), reflecting the incidence of the technological and electrical sub-systems (e.g. inverter, compressor, control units). Metals parts turn out secondary hotspots. In particular, steel makes up the largest mass share of the main unit but plays a less impact role (124.8 kg = 38% GWP), compared to copper and brass, distinguished by high emissions relative to their mass (36.5 kg = 22%GWP). By contrast, for the evaporator, aluminium dominates both in terms of material quantity and environmental impacts (90.2 kg = 67%GWP of evaporator only), due to its extensive use in structural parts. It is followed by fan and wiring (22.5 kg = 24%GWP). In both main units and evaporator, minor contributions arise from plastics, rubber and insulation, consistent with their limited mass shares. In either case, however, it is worth pointing out that all metals are modelled as fully virgin materials, due to lack of data about any recycled content, but including metal working. Moreover, further refinement could be achieved by modelling in detail the R410a refrigerant here used in

the heat pump (13 kg = 7%GWP total impacts), currently approximated using the most representative available dataset (*'Refrigerant R134a'*).

5.2 Water Loop fan Coil

The total GWP (A1-A3) of the Water Loop Fan Coil, referred to one complete unit with an overall mass of 34.7 kg, is estimated at 2.53E+02 kgCO_2e. From the hotspot analysis, the environmental profile is evidently dominated by metallic materials. Steel (15.2 kg = 36%GWP) and aluminium (9 kg = 36%GWP) represent the two main contributors to total impacts, modelled by comprising in both virgin material production and metal working, showing their significant mass and energy-intensive production. Secondary contributors rely on the complex equipment (4.1 kg = 11%GWP), including the compressor, copper and brass (2.1 kg = 8%GWP), mainly used for valves and hydraulic connections. Plastics, transport, insulation and refrigerant show minor contributions, even if – as happens for the Heat Pump – refined results could be achieved by modelling the R290 refrigerant used in the Water Loop Fan Coil (0.88 kg = 0.6%GWP), now approximated using the only available dataset (*'Refrigerant R134a'*).

5.3 Multi Converter

The total GWP (A1-A3) of the Multi Converter, referred to one complete system having a total mass of 254.6 kg, stands at 1.59E+03 kgCO_2e. The GWP hotspot analysis shows that the major contribution is allocated to steel (147 kg = 35%GWP), mainly used for the mechanical and structural elements and modelled by assuming 80% recycled content, as declared by the manufacturer, including the associated metal working process. Complex equipment, despite the smaller mass consisting essentially of electronics, represent similarly relevant share (47.6 kg = 33%GWP), highlighting the high material and processing intensity embedded in electronic assemblies, including sensing cards, digital cards, power boards and control boards. In third place, there is aluminium (32 kg = 16%GWP), also used for the mechanical parts but modelled with 40% recycled content, as declared by the manufacturer. It is followed by copper (16 kg = 10%GWP), considering virgin material production and reflecting its use in electrical connection and cabling. Plastic (12 kg = 3%GWP) and transport account for minor shares of total impacts.

6 Ongoing Effort to Advance Embodied Emission Reliability

Among the results, metals clearly emerge as major contributors to embodied emissions, due to their extensive use and energy-intensive production. Rather to simply suggest cutting down metals use or to find alternative materials (where structurally feasible), the findings emphasize the need to improve data quality, through more transparent information on material composition, recycled content and processing routes, supported by increased supply-chain traceability. In addition, to advance the reliability of embodied emissions modelling, electronics also deserves particular attention, given their disproportionately high impacts compared to their weight, due to the presence of precious metals, system complexity and energy-intensive manufacturing processes. In these instances, even small miscalculations in the inventory data or modelling inaccuracies may significantly influence the environmental results.

However, the study acknowledges several limitations. As first, the modelling primarily accounts for material flows, capturing only partially the working processes and excluding production waste and packaging, because of the lack of primary data. While some assembly phases may involve relatively minor impacts, there are greater uncertainty for complex sub-components, for which upstream production processes are often difficult to trace and quantify. The second constraint is that, where necessary, proxy datasets (e.g. refrigerants) and simplified assumptions (e.g. transport) were adopted, becoming areas for future refinement [11–13] as data quality improves and additional primary information becomes available. The challenge is in the intrinsic complexity of technical building systems, often comprising hundreds of sub-components. Manufacturers typically act mainly as assemblers, sourcing components from fragmented and geographically dispersed supply chains [14], with limited knowledge of upstream processes and little influence beyond supplier selection. This results in often unavailable key information for sub-components, making the collection of primary data particularly demanding and inevitably leading to simplification in LCA modelling. Furthermore, the cradle-to-gate boundary excludes downstream phases, including transport to site, installation, use, maintenance and end-of-life processes [15], which will be addressed in future analyses to provide a more comprehensive life cycle perspective.

In this context, improved supply chain mapping and traceability are essential for advancing the robustness of LCA results. Greater transparency at supplier level would reduce uncertainty and enhance reliability of embodied carbon assessments, supporting more informed low-impact decision-making across the building sector value chain.

Shifting from product-level to building-level assessment, the LCA of building systems appear increasingly critical. Indeed, many studies rely in practice on generic, not product-specific datasets, which often do not properly reflect the actual physical composition, technological specificity and technical performance of the systems under analysis. This restriction is mainly due to the limited availability of reference datasets, both in widely used databases, where many technologies remain insufficiently covered, and in Environmental Product Declarations (EPDs), which – although increasingly available – refer to specific products that may not match the system under analysis. Bypassing EPDs and looking to source the RE-SKIN building systems from databases, poor results are generated by both Ecoinvent and Ökobaudat. Fan Coil and Multi Converter are not directly represented: for the Fan Coil, the closest proxy is *'Decentralized ventilation units'*; for the Multi Converter, the only potentially comparable datasets are *'Inverter'* available in Ecoinvent with three different power (*0.5 kW, 2.5 kW, 500 kW*). They are yet all substantially different from the systems analysed. Conversely, Heat Pump case is more documented, but the comparison of the available datasets highlights significant variability in the estimated embodied impacts (Fig. 2), even when expressed for comparable nominal power. The RE-SKIN Heat Pump reflects a detailed air-water system-specific inventory, resulting in higher material intensity compared to generic datasets. Ecoinvent datasets rely only on brine-water systems, clearly scaling impacts with system capacity, but showing close order of GWP magnitude with RE-SKIN. Instead, Ökobaudat datasets, despite referring to same air-water technologies, display substantially lower impacts, due to different assumptions and system boundaries.

Overall, in building-level characterization the choice of datasets for technical systems can strongly influence the resulting LCA impacts, potentially affecting not only the magnitude of the results but also the identification of environmental hotspots and the derived decarbonization strategies. Accordingly, the importance of continuously improving the reliability of embodied emission for building systems, in order to capture the actual technological configuration and material intensity with sufficient granularity to avoid misrepresentation of environmental hotspots.

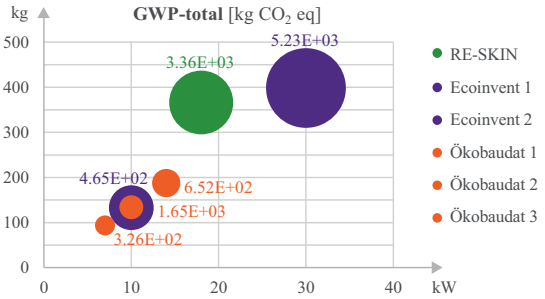


Fig. 2. Comparison of Heat Pump LCA datasets: nominal power (kW, x-axis) vs. system mass (kg, y-axis), with bubble size representing embodied emissions (GWP, A1-A3).

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Integrated AI Concept for Predicting Life-Cycle Performance and Circularity of Construction Products in Compliance with CPR 2024

Milos Knezevic[1(✉)], Ana Andabaka[2], Meri Cvetkovska[3], and Mirjana Laban[4]

[1] Faculty of Civil Engineering, University of Montenegro, Podgorica, Montenegro
knezevicmilos@hotmail.com
[2] Faculty for Economics and Business, University of Zagreb, Zagreb, Croatia
[3] Faculty of Civil Engineering, Ss. Cyril and Methodius University, Skopje, North Macedonia
[4] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

Abstract. This paper presents a methodological and conceptual framework for the development of an integrated AI model aimed at predicting the life-cycle performance and circularity of construction products in accordance with the new EU Construction Products Regulation (CPR 2024/3110). The proposed approach integrates artificial neural networks (ANN), life-cycle assessment (LCA), life-cycle costing (LCC), and material circularity indicators (MCI) to support automated prediction of environmental, technical, and circularity-related parameters required for Digital Product Passports (DPP).

The methodology focuses on defining relevant datasets, engineering ANN architectures, selecting LCA/LCC indicators aligned with CPR 2024 requirements, and establishing validation procedures based on regression-performance indicators such as RMSE and MAE. ANN models are intended to process datasets describing material composition, environmental profiles, production technologies, transport parameters, and durability characteristics in order to generate predictive outputs including global warming potential (GWP), recyclability rates, expected service life, and end-of-life scenarios.

The proposed framework demonstrates how AI-based tools may support manufacturers, designers, certification bodies, and regulatory institutions in addressing CPR 2024 requirements related to sustainability assessment, circularity performance, and digitalization of product information. The paper outlines the methodological basis for future development, validation, and implementation of integrated AI-driven sustainability assessment systems for construction products.

Keywords: Artificial Intelligence · CPR 2024 · Digital Product Passport · Life Cycle Assessment · Circularity

1 Introduction

The construction sector represents one of the largest consumers of natural resources and one of the major generators of waste, which is why the transition toward a circular economy has become an important priority of the European Green Deal and the

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Circular Economy Action Plan [1, 8, 9]. In this context, the new EU Construction Products Regulation, CPR 2024/3110, introduces new requirements related to sustainability assessment, transparency, circularity, and digital product information [2].

A particularly important role is assigned to the concept of the Digital Product Passport (DPP), which enables structured monitoring and traceability of technical, environmental, and circularity-related product characteristics throughout the entire life cycle [3]. At the same time, the growing complexity of data concerning material composition, production processes, durability, and end-of-life scenarios creates the need for advanced analytical tools capable of processing complex environmental and lifecycle datasets.

In this regard, artificial intelligence, especially models based on artificial neural networks (ANN), can provide significant support in modelling complex non-linear relationships between parameters that define the performance of construction products. By combining AI approaches with life-cycle assessment methods (LCA), life-cycle costing (LCC), and material circularity indicators (MCI), it becomes possible to develop an integrated predictive model based on AI methods for estimating key environmental and circularity indicators [11, 12].

Existing studies have mainly focused either on standalone life-cycle assessment approaches or on isolated applications of artificial intelligence in construction materials research. However, limited research has addressed the integration of ANN-based predictive systems with LCA, LCC, material circularity indicators, and Digital Product Passport requirements within the regulatory framework of CPR 2024.

The aim of this paper is to develop a methodological framework for predicting life-cycle performance and circularity of construction products in accordance with CPR 2024. The research question of the paper is how AI models can support automated prediction of life-cycle indicators and circularity metrics required within the new CPR 2024 regulatory framework. The paper focuses on defining relevant datasets, representative input and output parameters, ANN architecture principles, and validation procedures for future model implementation. Unlike previous studies that primarily address LCA methods or AI applications independently, this research proposes an integrated AI-driven framework that links predictive ANN models with life-cycle and circularity indicators within the regulatory context of CPR 2024 and Digital Product Passport implementation.

Since the objective of this study is to establish a methodological framework for future AI-assisted sustainability assessment of construction products, the implementation, training, and validation of the proposed model using real datasets are considered future research activities and are therefore outside the scope of the present paper. The focus of this research is on defining the architecture, data structure, predictive variables, and validation methodology required for subsequent model development and testing.

2 Regulatory Framework: CPR 2024 and Digitalization of Information on Construction Products

The new European Union Construction Products Regulation, CPR 2024/3110, represents a significant step toward greater sustainability, transparency, circularity, and digitalization of data related to construction products [2]. Compared to the previous CPR 305/2011 regulation, the new framework substantially expands the requirements

concerning environmental performance assessment, material circularity, lifecycle transparency, and the availability of digital information throughout the entire life cycle of construction products.

One of the central elements of CPR 2024 is the Digital Product Passport (DPP), defined as a structured digital repository of information related to product composition, environmental characteristics, technical performance during use, potential for reuse and recycling, and end-of-life management scenarios. The DPP concept is intended to improve transparency, traceability, and accessibility of product-related information across the entire construction value chain [3].

CPR 2024 also places stronger emphasis on life-cycle assessment methodologies and relies on instruments such as Environmental Product Declarations (EPD) and LCA indicators, including global warming potential, resource consumption, embodied energy, and waste generation [4–6]. The increasing quantity and complexity of sustainability-related data create the need for advanced digital and AI-based analytical tools capable of supporting automated processing and interpretation of environmental and circularity indicators required by CPR 2024.

3 Life-Cycle and Circularity Indicators of Construction Products

Assessment of construction product sustainability is commonly based on Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Material Circularity Indicators (MCI). LCA quantifies environmental impacts throughout the product life cycle, including production, transport, use, and end-of-life stages, while LCC evaluates the associated economic costs. MCI complements these approaches by assessing the circularity potential of products through indicators such as recycled content, durability, reuse potential, and recovery efficiency [4–7].

Within the proposed framework, key performance indicators include Global Warming Potential (GWP), life-cycle energy consumption, service life, recyclability rate, and Material Circularity Indicator (MCI). These indicators represent the target variables predicted by the ANN model and are aligned with sustainability and circularity requirements introduced by CPR 2024.

4 Conceptual Model of the Integrated AI System

The proposed integrated AI model combines artificial neural networks (ANN), life-cycle assessment (LCA), life-cycle costing (LCC), and material circularity indicators (MCI) to predict sustainability and circularity performance of construction products based on material composition, manufacturing processes, environmental profiles, transport characteristics, and durability parameters. The overall structure and data flow of the proposed framework are presented in Fig. 1.

As illustrated in Fig. 1, the proposed framework integrates material composition, manufacturing processes, LCA datasets, and durability-related information as input variables for ANN-based predictive modelling. The system combines ANN, LCA, LCC, and MCI to generate sustainability and circularity indicators that can be incorporated into Digital Product Passport systems in support of CPR 2024 implementation

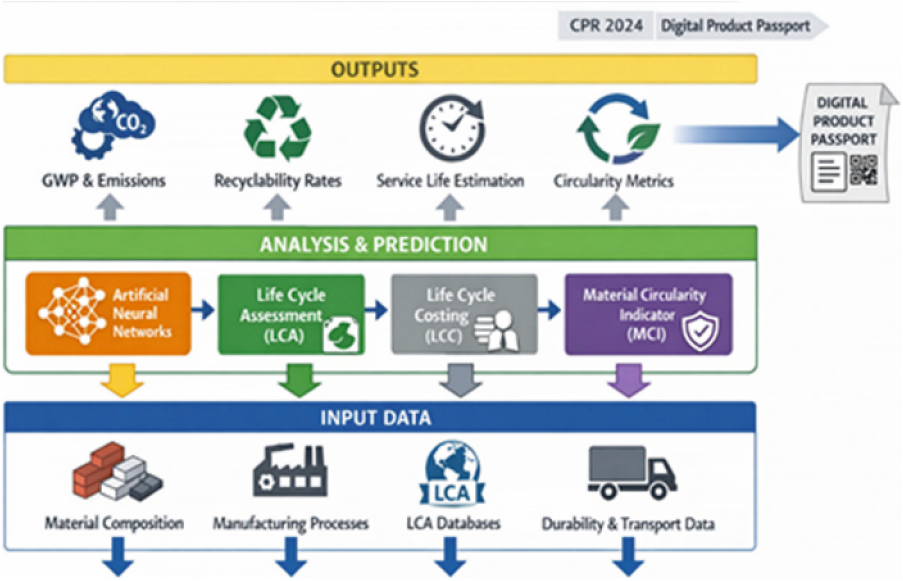


Fig. 1. Conceptual framework of the integrated AI–LCA–DPP model for predicting life-cycle performance and circularity of construction products in support of CPR 2024 requirements.

5 Methodology for the Development of the AI Model

The development of the proposed integrated AI model is based on a multi-phase methodological approach that includes identification of relevant datasets, definition of representative input and output parameters, development of artificial neural network architecture, and establishment of procedures for validation and evaluation of model performance. The proposed methodology is intended to provide a technically feasible framework for future implementation of AI-assisted sustainability assessment systems within the CPR 2024 regulatory context.

5.1 Structure and Data Sources

The first phase of the model development process refers to the identification, collection, and structuring of datasets capable of describing the environmental, technical, and circularity-related characteristics of construction products throughout their life cycle. The methodology foresees the use of data derived from Environmental Product Declarations (EPDs), LCA databases, technical product specifications, and datasets related to construction materials and manufacturing processes.

Potential data sources may include databases such as Ecoinvent, One Click LCA, EC3, and publicly available EPD repositories. The expected output parameters include global warming potential (GWP), energy consumption over the life cycle, estimated service life of the product, recycling and reuse rates, material circularity indicators, and end-of-life management scenarios [4–6].

For illustrative purposes, the proposed framework assumes datasets derived from Environmental Product Declarations (EPDs) and LCA repositories containing several hundred Environmental Product Declaration records representing concrete, steel, timber, insulation materials, and other major construction product categories. Such datasets are expected to provide sufficient variability for training and evaluating ANN-based prediction models within the proposed framework.

Based on these datasets, the key input parameters of the model are defined, including material composition (share of different components), type of production technology, energy requirements of manufacturing processes, transport distances and transport modes, physical and mechanical material properties, durability parameters, resistance to degradation, and recycled material content.

Table 1 presents the proposed structure of ANN input and output variables used within the predictive framework.

Table 1. Proposed structure of ANN input and output variables

Category	Variable	Description
Input	Material composition	Share of virgin and recycled materials (%)
Input	Manufacturing energy	Energy consumption during production (MJ/kg)
Input	Transport distance	Transport distance from production to site (km)
Input	Transport mode	Road, rail, sea, or combined transport
Input	Density	Material density (kg/m^3)
Input	Mechanical properties	Strength and durability characteristics
Input	Service-life parameters	Expected durability and degradation resistance
Input	Recycled content	Percentage of recycled material (%)
Output	Global Warming Potential (GWP)	kg CO_2 eq
Output	Life-cycle energy consumption	MJ
Output	Service life prediction	Years
Output	Recyclability rate	%
Output	Material Circularity Indicator (MCI)	Dimensionless index

The proposed dataset structure provides a preliminary basis for ANN training and enables prediction of key environmental and circularity indicators required for CPR 2024 compliance and Digital Product Passport implementation.

The preliminary structure of the ANN training dataset is expected to contain approximately 10–15 representative input parameters describing material composition, manufacturing processes, transport characteristics, and durability properties of construction

products. The proposed dataset structure represents a simplified but technically feasible basis for future ANN model training and sustainability prediction tasks.

5.2 Architecture of Artificial Neural Networks

For the development of the predictive model, a Multilayer Perceptron (MLP) artificial neural network architecture is proposed due to its ability to model complex non-linear relationships between multiple input and output variables. The preliminary ANN architecture consists of an input layer containing approximately 10–15 neurons corresponding to product-related parameters, two hidden layers with 24 and 16 neurons respectively, and an output layer generating predictions of key sustainability and circularity indicators, including Global Warming Potential (GWP), life-cycle energy consumption, service life, recyclability rate, and Material Circularity Indicator (MCI).

The proposed network is intended to be trained using the backpropagation algorithm and the Adam optimization method. ReLU activation functions are proposed for the hidden layers, while linear activation functions are applied in the output layer to support regression-based prediction tasks. The proposed ANN configuration represents a preliminary methodological framework intended for future implementation, calibration, and validation using real-world datasets derived from Environmental Product Declarations (EPDs), LCA databases, and technical product specifications.

5.3 Validation and Evaluation of Model Performance

In order to ensure reliability and scientific validity of the proposed model, the application of different methods for evaluation of model performance is foreseen.

The validation methodology may include:

- splitting datasets into training and testing subsets,
- application of k-fold cross-validation methods,
- evaluation of prediction errors using statistical indicators such as RMSE, MAE, and coefficient of determination (R^2).

Additionally, the methodology foresees implementation of regularization and overfitting-prevention techniques, including early stopping procedures and dropout regularization methods during ANN training. Such an approach enables assessment of the model's capability to generate reliable predictions and to generalize prediction results on datasets not previously used during the training process.

A proof-of-concept implementation using datasets derived from EPD repositories and LCA databases is planned as the next phase of the research in order to evaluate model feasibility, prediction accuracy, and practical applicability.

6 Discussion: Potential Application of AI Models within the CPR 2024 Framework

The application of integrated AI models may provide significant benefits for stakeholders involved in the development, assessment, and regulation of construction products [12]. For manufacturers, AI-assisted analytical tools can support faster evaluation of environmental and circularity performance during product development, enabling optimization

of material composition, production technologies, embodied carbon, recyclability, and resource efficiency [8]. At the same time, certification bodies and regulatory institutions may benefit from automated analysis and interpretation of sustainability-related data, improving transparency, consistency, and efficiency of construction product assessment within the CPR 2024 framework.

Despite these advantages, several limitations should be considered. The reliability of AI predictions depends on the quality, consistency, and availability of training datasets, while significant variations among Environmental Product Declarations (EPDs), life-cycle datasets, product categories, and geographical regions may affect model performance. In addition, the lack of standardized datasets for certain construction products remains a challenge for achieving high prediction accuracy and generalization capability. Nevertheless, the proposed framework demonstrates considerable potential for supporting sustainability assessment and circularity evaluation of construction products in accordance with CPR 2024 requirements.

7 Conclusion

The transition of the construction sector toward a circular economy requires the development of advanced methodological and digital tools capable of supporting assessment of environmental and circular performance of construction products. The new EU Construction Products Regulation (CPR 2024/3110) introduces significantly expanded requirements regarding transparency of information, lifecycle impact assessment, sustainability reporting, and digitalization of product data through the concept of Digital Product Passports [1, 8].

This paper presents a methodological framework for the development of an integrated AI model that combines artificial neural networks with life-cycle assessment methods (LCA), life-cycle costing analysis (LCC), and material circularity indicators (MCI). The proposed framework is intended to support development of predictive systems capable of estimating key environmental and circularity-related performance indicators of construction products based on data associated with material composition, manufacturing processes, transport characteristics, and durability parameters.

The proposed methodological framework demonstrates the potential applicability of AI technologies in supporting implementation of CPR 2024 requirements and future Digital Product Passport systems. Integration of AI-assisted analytical tools could contribute to more efficient development of sustainable construction products, optimization of material flows, improved certification procedures, and increased transparency and traceability of sustainability-related product information within the construction sector.

The research additionally contributes to the emerging field of AI-supported sustainability assessment of construction products within the regulatory context of CPR 2024 by proposing an integrated framework that links ANN predictive modelling with lifecycle and circularity indicators.

Although experimental validation is outside the scope of the present study, the proposed framework provides a technically feasible and structured basis for future implementation and testing of AI-assisted sustainability assessment systems using real-world construction product datasets.

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Recycled Concrete and Impacts in Building Life Cycle Assessment

Gerald Lendecker[1(✉)], Jan Pesta[2], Nika Trubina[2], Carlos Beltran-Velamazán[3], Marta Gómez-Gil[3], and Teresa Blázquez[4]

[1] FH Upper Austria, Austria and ETH, Zürich, Switzerland
gerald.leindecker@fh-wels.at
[2] UCEEB, Czech Technical University in Prague, Třinecká, Czech Republic
[3] Built4Life Lab, I3A, Universidad de Zaragoza, Zaragoza, Spain
[4] IUACC-ETSA, Universidad de Sevilla, Seville, Spain

Abstract. The construction sector has a major environmental impact due to high resource consumption, energy use, and carbon emissions. Among construction materials, concrete is a major contributor to GHG emissions. Optimizing logistics—such as increasing recycling and reuse or sourcing local materials—can significantly reduce concrete's environmental footprint and improve construction sustainability. Furthermore, transport-related emissions stem from raw material extraction and delivery, concrete mixing and distribution, and construction and demolition waste management. Life Cycle Assessment (LCA) is a key method for evaluating these impacts. This paper presents the application and results of a new calculation tool within two selected case studies that highlights the role of transport within a full LCA and includes the benefits of reusing building materials in a circular approach by reducing reliance on virgin resources and securing more circular supply chains. Using the tool, we examine the environmental and economic impacts of these different scenarios, focusing on recycled concrete versus landfill disposal. A structured calculation matrix incorporates key factors such as concrete composition, transport distances, and CO_2 emissions. By applying relevant national standards, the divergent results will be analyzed and discussed. The systematic assessment of these parameters will identify opportunities to improve environmental performance.

Keywords: Circular Economy · Recycled Concrete · Circular Indicator · Parameters for Circular Assessment · Standards

1 Introduction

The global construction sector is responsible for a substantial share of energy consumption and greenhouse gas (GHG) emissions, largely due to the extensive use of resource-intensive materials such as concrete [1].Cement production alone accounts for approximately 7–8% of global CO_2 emissions, making concrete a critical target for sustainability improvements. While significant research has focused on reducing emissions through material innovation, such as alternative binders and low-carbon cement,

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transport-related impacts remain under-examined. These impacts arise throughout the life cycle of concrete, including raw material extraction, production, distribution, and end-of-life waste management [2]. The transition toward a circular economy in construction—emphasizing reuse, recycling, and reduced reliance on virgin materials—offers considerable opportunities to mitigate environmental impacts [3]. However, the benefits of circular strategies depend heavily on logistical factors such as transport distances and infrastructure availability [4].This study aims to evaluate the environmental and economic implications of transport within a full LCA framework according to CEN Standard EN 15978 [5]. A dedicated calculation tool has been developed within the framework of the COST Action CA21103CircularBand applied to two case studies to assess different scenarios, with a particular focus on recycled concrete versus landfill disposal.

2 Methodology

2.1 Calculation Tool

A calculation tool was developed to evaluate environmental impacts across different scenarios. Transport is explicitly modeled across all stages using distance-based emission factors. The tool incorporates a structured matrix including:

- Material composition (cement, aggregates, recycled content)
- Transport distances and logistics chains
- CO_2 emission factors (kg CO_2 per ton-kilometer)
- Energy consumption
- Cost parameters (transport, processing, disposal fees)

The tool enables scenario comparison and sensitivity analysis.

2.2 System Description

The analysis encompasses all relevant life cycle stages, namely: (i) the product stage, (ii) the use stage, and (iii) the end-of-life stage. In addition, potential benefits and loads beyond the system boundary are considered within the framework (Fig. 1)

The product stage includes material production processes, comprising raw material extraction (A1), transport to manufacturing facilities (A2), and the production of construction products (A3). The construction process stage accounts for the transportation of materials to the construction site (A4) and the environmental impacts associated with installation activities (A5), including energy use and emissions.

As this study focuses on specific building components—particularly concrete—rather than a complete building system, a simplified approach is adopted that considers only embodied emissions and energy. Operational energy and water use (B6 and B7) are excluded. Furthermore, differences in material service life relative to the overall building lifespan are not explicitly modeled; therefore, replacement and refurbishment processes (B4 and B5) are not included.

The end-of-life stage comprises deconstruction processes (C1), transport of materials to waste processing facilities (C2), waste treatment operations (C3), and final disposal

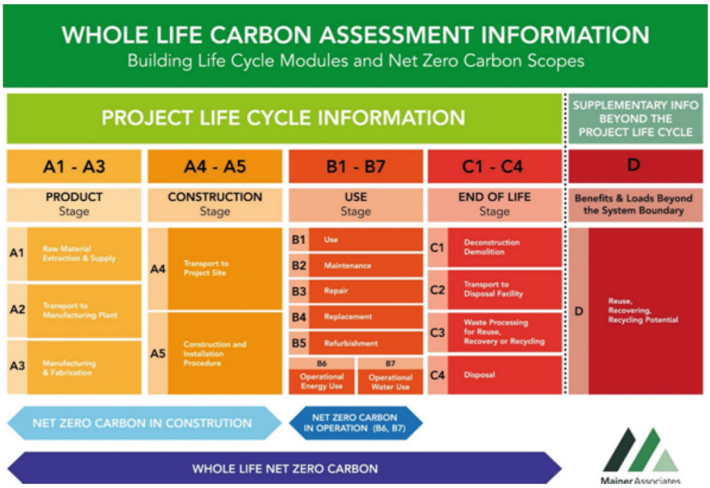


Fig. 1. Model of the life cycle of buildings and components based on EN 15978-1

(C4). Beyond the system boundary, Module D accounts for potential net environmental benefits associated with reuse and recycling.

Given that the primary objective of this study is to evaluate the influence of transportation distances on the environmental performance of conventional and recycled concrete, the analysis focuses on modules with variable parameters. Modules A3 to C1 are treated as constant baseline values across the compared scenarios. The assessment therefore emphasizes processes related to concrete production, transport from varying source locations, recycling operations, and associated logistics. Additionally, the reduction in demand for virgin concrete is incorporated into the calculation model as an environmental credit.

2.3 Case Studies

To demonstrate the application of this life cycle assessment approach, two representative case studies are analyzed (Fig. 2). These compare a conventional linear concrete production model (Scenario A) with a circular alternative incorporating recycled aggregates (Scenario B).

Case Study A (Linear Scenario): Conventional concrete production with landfill disposal of construction and demolition waste (CDW). Scenario A represents the life cycle assessment (LCA) of conventional concrete, reflecting current standard practice. It assumes the production of concrete exclusively from virgin materials and its disposal in a landfill at the end of its service life. This scenario follows a linear life cycle model, without the incorporation of circularity principles such as reuse or recycling.

Case Study B (Circular Scenario): Use of recycled aggregates and closed material loops.

Scenario B represents an alternative LCA approach incorporating circular economy principles. In this scenario, concrete contains a defined proportion of recycled aggregates and is further processed at the end of its life cycle to produce new recycled concrete.

Compared to Scenario A, Scenario B includes additional transportation processes (A2), specifically for the delivery of recycled materials from recycling facilities to concrete production plants, alongside the transport of primary raw materials.

The end-of-life stage also differs substantially. Instead of landfill disposal, this scenario includes transport to recycling facilities, material recovery processes, and subsequent reuse. These processes correspond to modules C2 and C3, as well as Module D, which accounts for benefits beyond the system boundary through avoided impacts associated with the substitution of virgin materials.

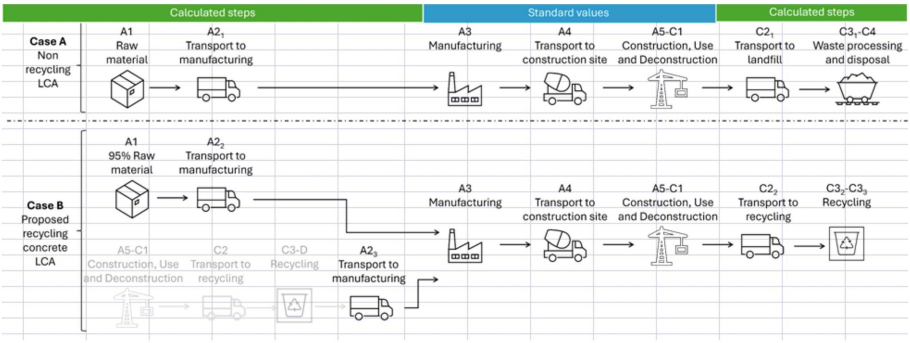


Fig. 2. Manufacturing process for two scenarios based on LCA modules: (A) traditional concrete production and (B) concrete production with recycled aggregate

In a realistic case study, transportation distances were implemented into the matrix according to the following table (Table 1):

Table 1: Actual distance used in the calculation.

Distances	Km	Relation to case
Raw material -cement- to concrete production site	11	A2–1 (case A) and A2–2 (case B)
Raw material -gravel- to concrete production site	24.5	A2–1 (case A) and A2–2 (case B)
Raw material -sand- to concrete production site	24.5	A2–1 (case A) and A2–2 (case B)
Recycling center to concrete production	5	A2–3 (case B)
Concrete production to construction site	11.2	A4 (both cases)
Construction site to landfill	35.4	C2–1 (case A)
Construction site to recycling center	11	C2–2 (case B)

The ratio used in the example is cases study A (100% virgin concrete) versus cases study B (95% virgin concrete and 5% recycled concrete aggregates)

2.4 Assumptions and Parameters

Key variables include:

- Transport distances
- Mixture of the concrete
- Transport mode (primarily truck-based)
- National standards governing recycled material use

These parameters were selected to reflect realistic construction practices and regulatory frameworks.

The life cycle inventory is based on datasets from the Ecoinvent v3.7. Impact categories are defined in accordance with the EN 15804.A functional unit of 1 m^3 of concrete with a compressive strength of 25 MPa is adopted. The concrete mix design follows standard industry practice and consists of: 1 part cement (Portland cement CEM II/A-S 32.5), 2 parts sand (30.77%), 3 parts gravel (46.15%), and 0.5 parts water (7.69%).

Taking into consideration recent research findings [6], the amount of additional cement for recycled concrete is feed into the calculation with the factor of 8% of additional cement in the mixture (Table 2).

Table 2. Composition of concrete (prime) and with the use of recycled aggregates.

Composition of concrete	Prime	Recycled aggregates
Overall	2350 kg/1 m^3	2350 kg/1 m^3
Prime raw material	2065 kg/1 m^3	1440 kg/1 m^3
Secondary raw material	– kg/1 m^3	600 kg/1 m^3
Cement	285 kg/1 m^3	310 kg/1 m^3

Energy consumption associated with the recycling of aggregates is incorporated using datasets for waste concrete treatment and sorting processes available in the Ecoinvent database. For the transportation analysis, freight transport is modeled using a 16–32 metric ton lorry (EURO 4 standard), as specified in the database. A CO_2 neutral transport mode would neutralize the negative effect of transport distance.

2.5 Methodology Used for Calculation

To quantitatively evaluate the environmental impacts of both scenarios, Global Warming Potential (GWP) is calculated for each life cycle stage. The assessment distinguishes between the linear system (Scenario A) and the circular system (Scenario B), capturing

the contributions of production, transportation, end-of-life processing, and potential benefits beyond the system boundary.

$$GWP_{case\ A} = A1 + A2_1 + C2_1 + C3_1 + C4 \tag{1}$$

$$GWP_{case\ B} = A1 * P_{recycled} + A2_2 + A2_3 + C2_2 + C3_2 + C3_3 \tag{2}$$

$$A1 = \sum_{1}^{M} M_{material} * GWP_{material} \tag{3}$$

$$M_{material} = \frac{P_{material}}{100} * 1000 * M_{concrete} \tag{4}$$

$$A2_1 = \sum_{1}^{M} \frac{M_{material}}{1000} * GWP_{transport} * D_{material} \tag{5}$$

$$A2_2 = \sum_{1}^{M} \frac{M_{material}}{1000} * P_{recycled} * GWP_{transport} * D_{material} \tag{6}$$

$$A2_3 = GWP_{transport} * D_{concrete\ production} \tag{7}$$

$$C2_1 = GWP_{transport} * D_{landfill} \tag{8}$$

$$C2_2 = GWP_{transport} * D_{recycling\ center} \tag{9}$$

$$C3_1 + C4 = GWP_{collection\ for\ final\ disposal} * M_{concrete} + GWP_{final\ disposal} * M_{concrete} \tag{10}$$

$$C3_2 + C3_3 = GWP_{sorting\ plant} * M_{concrete} + GWP_{recycling} * M_{concrete} \tag{11}$$

3 Results

3.1 Result of the 2 Cases: Kg CO_2 eq (Table 3)

Table 3: Comparison of Case A versus case B

	Case A	**Per ton of new concrete**					**Total per ton**
	%	**A1**	**$A2_1$**	**$C2_1$**	**$C3_1$**	**C4**	
Virgin Con.	100	139.48	9.90	5.84	14.04	8.44	177.71 kg CO_2 eq
	Case B	**Per ton of recycled concrete**					**Total per ton**
	%	**A1**	**$A2_2$**	**$A2_3$**	**$C2_2$**	**$C3_2$**	**$C3_3$**	
Virgin Con.	95	132.51	9.40	0.04	5.64	13.83	8.22	169.65 kg CO_2 eq
Recycled Con.	5							

3.2 Environmental Performance

The analysis shows that transport contributes significantly to total lifecycle emissions. Key findings include:

- Transport distance is an influential factor influencing environmental impact
- Local sourcing and recycling significantly lower emissions
- Recycling efficiency and material quality influence environmental outcomes
- The vehicle-type related impact is relevant for the calculation

3.3 Waste Deposit and Distance as a Factor for Reuse, Including a Calculation

The use of non-recycled concrete, following the specified proportions and based on data from the Ecoinvent database, results in a GWP of 161.97 kgCO_2 eq per tonne of concrete, excluding the transportation phase. The use of 90% of non-recycled concrete and 10% of recycled concrete results in a GWP of 161.79 kgCO_2 eq per tonne of concrete, excluding the transportation phase. So initially, the gain without considering the distance is in fact 0.18 kg CO_2 eq per tonne of concrete.

When considering total GHG emissions, emissions increase by 0.001% or 0.01 kg CO_2 eq. for each additional kilometer across all categories (A2 and C2). An increase of 10 km leads to a 0.01% rise in GHG emissions from the concrete. If the additional distance to the recycling center reaches **11.30 km**, emissions increase, reaching 0.18 kg CO_2 eq per tonne of concrete, and the gain from using recycled concrete becomes neutralized. This means that this is the tipping point, when gains turn into losses. Regarding recycled concrete, when distance is not considered, the incorporation of 1% recycled material into the mix results in a reduction of GHG emissions by 0.011%, avoiding the release of 0.018 kg CO_2 eq per tonne of concrete. Consequently, with standard values accepted under European regulations ranging between 5% and 10% recycled content, savings of between 0.05% and 0.11% can be achieved, representing significant reductions in the environmental impact of concrete.

When transportation distances are considered, assuming equal distances, emission reductions remain largely unaffected. However, distance becomes a critical factor if the recycling facility is far enough away to negate the emission savings achieved.

If the calculation reduces the amount of additional cement for recycled concrete with the factor of 0% instead of 8% of additional cement in the mixture, then the tipping point would be at **77.18 km** of additional distance to the recycling center.

4 Discussion

The results emphasize the critical role of transport in the sustainability of concrete production and also the importance of improved concrete mixtures when using recycled aggregates [7]. While material innovations remain important, optimizing logistics can also provide substantial additional reductions in emissions.

Circular economy strategies, particularly the reuse of concrete materials, demonstrate clear environmental and economic benefits. However, these benefits are highly context-dependent and rely on local infrastructure and regulatory conditions.

The study also highlights the importance of national standards, which can either enable or constrain the use of recycled materials. Greater harmonization of standards could facilitate broader adoption of circular practices.

Limitations of this study include the use of generalized emission factors. The strength of the calculation matrix is that it uses case-sensitive data to get a quantitative answer on the exact savings or evenlosses overall in respect to its global warming potential.

The newly developed tool enables a precise assessment of the transportation stage by accounting for both associated gains and losses. In contrast to existing calculation methods, which typically estimate CO_2 emissions solely on the basis of transport distances, this tool facilitates a comprehensive evaluation aligned with the environmental performance assessment framework for buildings as defined in the EN 15978. Consequently, it supports the quantification of environmental impacts and benefits beyond the system boundary. This tool is in fact able to calculate potential net benefits from reuse or recycling in module D of the framework. (D).

This capability represents a significant advancement, effectively transforming the traditionally linear Life Cycle Assessment (LCA) encompassing pre-construction, construction, use, and end-of-life stages into a genuinely circular assessment process. Moreover, this tool is using real-world logistics data to replace assumed transport distances to get an exact assessment on a case-by-case approach.

5 Conclusion

This study demonstrates that transport is a key factor in the environmental and economic performance of concrete within a life cycle framework together with the concrete mixtures when using recycled aggregates. The application of a dedicated calculation tool reveals that the transport distance of all involved sites (not only the building site) strongly influences emissions, and circular supply chains and local sourcing are essential for reducing environmental impact.

Integrating transport considerations into LCA tools can support more informed decision-making and promote sustainable construction practices.

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LCA and LCEA of an Industrial Building: A Volvo Case Study

Giovanna Ferreira Alves(✉), Milena Franco Fagundes, and Sergio Fernando Tavares

Civil Engineering Post-Graduate Program (PPGEC), Federal University of Parana, Centro Politécnico, Curitiba 81531-980, PR, Brazil
giovannaferreira@ufpr.br

Abstract. The pursuit of more sustainable buildings has gained prominence in the industrial sector, where energy demand tends to be high from the early stages of the project through the operational phase. Thus, reduction of embodied energy represents a strategic drive for reducing environmental impacts and optimizing the use of natural resources. In this study, Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) are applied to an industrial building of Volvo in Brazil to (i) assess embodied energy demand at the first life-cycle stage, (ii) identify impact hotspots at this stage, and (iii) propose reduction strategies based on the results. The methodology adopted in this study follows the guidelines established by the international standards ISO 14040 and ISO 14044, which address LCA, as well as the European standards EN 15804 and EN 15978, which are specific to the environmental assessment of buildings. A BIM model was used to extract materials inventory and EPDs were used in analysis for reduction strategies. The results show that steel and concrete are the most impactful materials, and there are few reduction strategies available, since Brazil is a country where only a small number of companies evaluate the environmental impact of their products compared with other countries. However, the interpretation of these impacts, in turn, can support indicators such as carbon footprints, which are required for the issuance of carbon credits.

Keywords: Life Cycle Assessment · Life Cycle Energy Analysis · BIM · EPD

1 Introduction

The search for more sustainable buildings has gained prominence in the industrial sector, where energy demand tends to be high from the initial phases of the project through to operation. In this context, reduction of embodied energy represents a strategic vector for reducing environmental impacts and optimizing the use of natural resources.

The Life Cycle Energy Analysis (LCEA) is a methodological approach that allows quantifying embodied energy demand throughout all phases of the building, from raw material extraction and input manufacturing to the usage phase and end of life (Cabeza, 2014). This approach allows for the identification of the main embodied impact hotspots

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and supports the proposal of more efficient technical and operational solutions. An LCEA does not fully replace an LCA, but it is useful for more detailed analyses of the energy input variables throughout the lifecycle (Tavares et al., 2006). Thus, based on these analyses, significant environmental impacts such as CO_2 emissions, either full or equivalent, can be identified (Fay et al., 2000). The interpretation of these impacts, in turn, can underpin indices such as carbon footprints, which are requirements for issuing carbon credits.

Thus, in this study, LCEA is applied to the Warehouse P220 project, an industrial building of Volvo do Brasil Veículos S.A., located in the city of Curitiba, Paraná, Brazil. The objective is to assess embodied energy demand in the early stages of the life cycle, identify impact hotspots, and propose reduction strategies based on the results obtained. The scope of the analysis covers the pre-operational phase of the building's life cycle, stages A1 to A3, in accordance with the European Union standard EN15978: Environmental performance assessment of buildings. Operational energy use and operational energy efficiency were not assessed in this study. The functional units adopted are embodied energy demand, expressed in megajoules per square meter (MJ/m^2), and carbon dioxide emissions per square meter ($kg\ CO_2/m^2$).

2 Methodology

The methodology adopted in this study is divided into three stages. The first stage involves calculating the environmental impacts of the building analyzed using the calculation method proposed in Tavares's thesis (2006), complemented by the methodological update in the article by Tavares and Bragança (2016). Additionally, environmental inventory data from recognized sources were used, such as the Environmental Product Declarations (EPDs) from national and international suppliers, including Votorantim Cimentos, ArcelorMittal, Bauforumstahl, and ATIC (Technical Association of the Cement Industry) of Portugal. The calculations follow the guidelines established by the international standards ISO 14040 and ISO 14044, which address LCA, as well as the European standards EN 15804 and EN 15978, which are specific to the environmental assessment of buildings.

The LCEA structure presented here considers the initial stages of the building's life cycle: extraction and production of materials, including the embedded energy in raw material extraction, manufacturing, and industrial processing processes. These steps are described in the EN 15978 standard as A1, A2, and A3.

The evaluated metrics include embodied primary energy (MJ) and carbon dioxide emissions ($kg\ CO_2$). These indicators characterize the embodied environmental impacts associated with material production and processing in the early life-cycle stages.

The second stage of the methodology involves identifying impact hotspots, which are the processes and materials that concentrate the greatest impact throughout the building's lifecycle. Finally, the third and last stage of the methodology compared and analyzed the impact hotspots materials with market-available materials in search of better sustainability performance. The materials analysed in this section are concrete, steel, and cement. The cement was examined to determine if any type of cement offers better sustainability performance for use in concrete.

The building description is presented in Sect. 2.1. The impact calculation results are available in Sects. 3.1 and 3.2 of the Results section. The impact hotspots assessment is described in Sect. 3.3, and the comparative analyses are presented in Sect. 3.4. Sections 4 and 5 are Discussion and Conclusions, respectively.

2.1 Industrial Building Description

The building studied is the industrial warehouse named Warehouse P220, belonging to Volvo do Brasil Veículos S.A., located in Curitiba, Paraná, Brazil. The project has a constructed area of 4.431,46 m^2 and adopts a conventional construction system for industrial buildings. The foundation consists of a continuous flight auger pile, foundation blocks, and a concrete floor/slab. The vertical enclosures use concrete blocks with a metal-sheet finish, and the roof is formed by double-faced metal sheets with rock wool thermal insulation.

Figure 1 shows the 3D visualization of the building's BIM model. The project was provided by the company responsible for the project from design through renovation and construction.

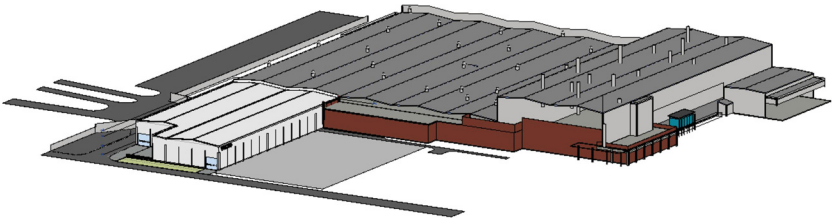


Fig. 1. 3D visualization.

The inventory for this project was compiled by extracting quantities from the BIM model and gathering data from the structural projects in .dwg format. The BIM model provided architectural design information alongside quantity tables for all materials. For the structural projects (reinforced concrete and steel structures), the .dwg file was supplied. Consequently, it was necessary to review all drawings and conduct a quantitative survey of the materials related to this discipline.

3 Results

3.1 Embodied Energy

Table 1 presents the materials used in the construction, their respective total embodied energy (EE) values, and the specific value per square meter of built area. The estimated total embodied energy of the building is 11.879.886,19 MJ, corresponding to 2.680,80 MJ/m^2. A36 steel is the material with the highest embodied energy, totaling 4.993.292,27 MJ, followed by concrete with a compressive strength of 30 MPa, with 3.565.751,94 MJ.

Table 1. Embodied energy values of materials (MJ).

Material	EE Total (MJ/m^2)	Percentage (%)	Cumulative Percentage (%)
Concrete fck = 30Mpa	3565751,94	30.02	30.02
Concrete fck = 40Mpa	409283,88	3.45	33.47
CA-25 Steel	271547,64	2.29	35.76
CA-50 Steel	1520531,91	12.80	48.56
A36	4993292,27	42.03	90.59
Concrete block 19 cm × 19 cm × 39 cm	90750,31	0.76	91.35
Ceramic tile cladding	6112,14	0.05	91.40
Paints	42401,18	0.36	91.76
Wooden doors	624,32	0.01	91.77
Gypsum board 70 cm × 70 cm	24541,30	0.21	91.98
Steel sandwich panel. Galvalume RAL9003, sheet thickness 0.43 mm	436515,52	3.67	95.65
Steel roof sheet TP25, pre-painted on both sides, thickness 0.5 mm	261657,88	2.20	97.85
Rock wool 50 mm	99643,33	0.84	98.69
Guardrail and handrail	2009,44	0.02	98.71
Mortar	141171,13	1.19	99.90
Steel and iron	14052,00	0.12	100.00
Total	**11879886,19**		
Total per m^2	**2.680,8**		

Regarding the percentage distribution of embedded energy among the ten main materials, A36 steel accounts for 42.03%, followed by concrete with a compressive strength of 30.02 MPa at 30%, CA-50 steel at 12.80%, and steel sandwich roofing panels at 3.67%. These four materials together make up 88% of the building's total embedded energy.

Embodied energy, based on the materials' life-cycle stages, can be divided into production, transportation, and waste losses. It is observed that the production, exploration, and transportation of inputs (Stage 1) account for approximately 88% of the total embodied energy, underscoring their significance for the project's energy impact.

3.2 Embodied CO_2

Regarding greenhouse gas emissions, Table 2 presents the values of carbon dioxide (kg CO_2) embedded in each material. The results follow a similar trend to the embedded energy, with concrete and steel being the main emitters.

Table 2. Embodied CO_2 results for construction materials

Material	Totals (kg CO_2)	Percentage (%)	Cumulative Percentage (%)
Concrete fck = 30Mpa	328499,15	41.09	41.09
Concrete fck = 40Mpa	39234,49	4.91	46.00
CA-25 Steel	3611,79	0.45	46.45
CA-50 Steel	23780,68	2.97	49.42
A36	381017,90	47.66	97.08
Concrete block 19 cm × 19 cm × 39 cm	3639,99	0.46	97.54
Ceramic tile cladding	314,01	0.04	97.58
Paints	3122,00	0.39	97.97
Wooden doors	22,30	0.00	97.97
Gypsum board 70 cm × 70 cm	1374,55	0.17	98.14
Steel sandwich panel. Galvalume RAL9003, sheet thickness 0.43 mm	7900,93	0.99	99.13
Steel roof sheet TP25, pre-painted on both sides, thickness 0.5 mm	3884,49	0.49	99.62
Rock wool 50 mm	200,57	0.03	99.64
Guardrail and handrail	36,37	0.00	99.65
Mortar	2555,20	0.32	99.97
Steel and iron	254,34	0.03	100.00
Total	**799448,76**	**100.00**	
Total per m^2	**180,40**		

A36 steel appears as the main emitter (47.66%), followed by concrete with fck = 30 MPa (41.09%), concrete with fck = 40 MPa (4.91%), and CA-50 steel (2.97%). Together, these four materials account for more than 96% of the embedded CO_2.

3.3 Impact Hotspots

The analysis of embedded energy and CO_2 emissions data helps identify hotspots, which are the processes and materials with the greatest impacts throughout the building's life

cycle. The results show that the main critical points are related to the industrial production of concrete (fck = 30 MPa and fck = 40 MPa), A36 steel, and CA-50 steel, which together account for more than 88% of the total embedded energy and over 96% of CO_2 emissions.

These materials exhibit high energy intensity during their manufacturing stages, involving processes such as burning, thermal transformations, transportation of inputs, and fossil fuel use. Additionally, their high mass and volume within the structure's composition reinforce their weight in the overall life-cycle impact. The production stage—especially cement, aggregates, and rolled steel—is the largest contributor to the project's total energy load, accounting for approximately 88% of the embedded energy, as shown in Table 1.

3.4 Comparative Analysis of Kg CO_2 for Impact Hotspots

The kg CO_2 data for the most impactful materials were collected from their respective EPDs. For CA-50 steel, the EPD published by ArcelorMittal was used. For A36 steel, the EPD published by Bauforumstahl was used. For concrete, EPDs published by Votorantim Cimentos were used. And for cements, EPDs published by Votorantim Cimentos and ATIC were used.

The comparison between the materials was made using the inventory extracted from the project. Thus, the mass (for steels) and the volume (for concrete) remained constant across the comparison scenarios. The values obtained are in kg CO_2 equivalent.

A36 steel is the material with the greatest environmental impact in the project, responsible for more than 40% of the embedded CO_2 emissions. Therefore, it is recommended to reevaluate the use of this material as outlined in the project. As a more sustainable alternative, adopting ArcelorMittal's XCarb steel is recommended, as its production has significantly lower embedded CO_2 emissions. This is due to the use of recycled scraps and the process's exclusive use of renewable energy.

Replacing CA-50 steel with ArcelorMittal's XCarb steel lowers embedded CO_2 by about 25%. For the A36 steel used in the metal structure, the reduction is even greater, exceeding 85%, due to its larger mass in the building.

Among potential scenarios to enhance the environmental performance of concretes, the SPECTRA 40 concrete from Votorantim Cimentos in São Paulo stands out as a promising option. This concrete uses a single mix design throughout the structure, simplifying the pouring process and reducing on-site concrete and steel consumption (VOTORANTIM CIMENTOS, 2025).

The SPECTRA 40 concrete from São Paulo showed better sustainability results than the fck = 40 MPa concrete, reducing CO_2 emissions by more than 5,000 kg, equivalent to a 13% decrease.

Finally, a comparative analysis between cements CP II, CP III, and CP IV was conducted. The analysis evaluates the cement content in 1 m^3 of concrete with a compressive strength of 30 MPa. Thus, for concrete with fck = 30 MPa, 265 kg of CP II, 300 kg of CP III, and 300 kg of CP IV were used. The values for CP II and CP IV were provided, and the authors adopted the value for CP III.

To develop the cement analysis, the EPDs provided by Votorantim Cimentos and ATIC Portugal were used. The Portuguese EPD was used for CP IV because there is no published EPD with a Brazilian scope for this cement.

Among the evaluated cements, CP III shows the best sustainability performance, with values 40% lower than CP II and 49% lower than CP IV.

4 Discussion

The EPD used for the concrete is from Votorantim Cimentos, while the EPDs for steel are from ArcelorMittal and Bauforumstahl. Votorantim Cimentos is the only company to have published an EPD for this material with a scope in Brazil, just as ArcelorMittal is the only company to have an EPD for steel with a partial scope in Brazil. The Bauforumstahl EPD was used as a reference for A36 steel despite the European scope, because there is no published EPD for this material with a Brazilian scope. The ArcelorMittal EPD for XCarb steel was used as a reference, despite its scope being limited to Luxembourg and Spain. Additionally, the geographic scope of ArcelorMittal's steel EPD must be considered. This EPD presents the environmental impact of the material in the pre-operational phase (A1-A3) in Morocco, while the end-of-life phases (C-D) have a global scope. Therefore, the document is not fully applicable in Brazil.

The results show that, for steels, the best alternative is ArcelorMittal's XCarb product. This material has its entire production process carried out using renewable energy and uses recycled raw materials.

Regarding concrete with fck = 40 MPa, it is recommended to use SPECTRA 40 concrete from Votorantim Cimentos in São Paulo, as it offers better sustainability performance. Spectra is a type of concrete with a single mix design, developed to meet all stages of structural construction, thereby simplifying and making the pouring process more efficient. Its versatility contributes to the longevity of the concrete structure and allows for reduced use of materials such as concrete and steel. As an additional benefit, using Spectra can result in 3% to 4% savings on the total cost of the structure.

The assessment of the cements aimed to compare the sustainability performances per cubic meter of concrete with a compressive strength of 30 MPa. The results show that CP III performs best compared to CP II and CP IV. To achieve this result, a CP III content of 300 kg per cubic meter of concrete was established. This value was adopted by the authors. It is recommended to validate this number with a specialist to confirm the results.

Furthermore, the assessment of the presented cements is insufficient to draw a comprehensive conclusion about sustainability because the other materials that make up the concrete must also be evaluated, including aggregates and possible additives.

The results and suggested alternatives are related to the sustainability performance of the materials. However, substituting these materials involves other analyses from different specialities, as structural analysis. It is recommended to have a structural expert in reinforced concrete and metal structures evaluate the substitution of these materials. Additionally, if the substitution increases the quantities of these materials, a future sustainability analysis should be conducted.

5 Conclusions

In the developed study, the embodied primary energy demand (MJ) and embodied CO_2 emissions (kg CO_2) associated with building materials were evaluated.

The results show that the most impactful materials are A36 and CA-50 steels, and concretes with fck = 40 MPa and fck = 30 MPa, as they have the highest EE and the most embedded CO_2, due to their high-energy production processes and their significant contribution to the project in mass and volume.

The continuation of this study aims to develop an LCA for the building's use, operation, and end-of-life phases. The analyses of the use and operation phases involve energy-efficiency studies that evaluate energy generation and systems such as lighting, air conditioning, and machinery. The end-of-life phases involve circular-economy studies, including the optimisation of waste utilisation and opportunities for recycling and material recovery, using digital documentation such as Material Passports.

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Methodological Framework for the Environmental Assessment of an Innovative Terracotta-Based Modular System for Green Roofs and Walls Applications

Ludovica Marcelli[1](✉), Elisa Di Giuseppe[1], Federico Brilli[2], Francesca Rapparini[3], and Marco D'Orazio[1]

[1] Dipartimento di Ingegneria Civile Edile e Architettura, Università Politecnica delle Marche, Ancona, Italy
l.marcelli@pm.univpm.it

[2] Istituto per la Protezione Sostenibile delle Piante (IPSP), Consiglio Nazionale delle Ricerche (CNR), Sesto Fiorentino, Italy

[3] Istituto per la BioEconomia (IBE), Consiglio Nazionale delle Ricerche (CNR), Bologna, Italy

Abstract. Green roofs and green façades are widely recognized as effective Nature-based Solutions (NbS), offering opportunities to advance sustainable construction practices. However, these systems often involve technologically complex multilayer assemblies and require high maintenance. This study focuses on an innovative modular clay tile designed to accommodate a low-thickness substrate layer for plant growth, providing a lightweight and easily installable solution. Since this system represents a novel approach compared with conventional NbS technologies, its environmental implications remain unexplored. Therefore, a methodological life-cycle framework was developed to support the environmental evaluation of these hybrid systems that operate across regulatory and functional boundaries between clay construction products and vegetative components. The defined system boundaries include both tile manufacturing and use-stage processes associated with the vegetated system. The implementation of a pilot production line with detailed flow accounting allows the collection of foreground data on the tile manufacturing process. These data are integrated with laboratory experiments on the performance of substrate and vegetation layers to estimate, under controlled environmental conditions, CO_2 storage processes relevant to the overall life cycle environmental profile. The incorporation of these empirical datasets strengthens the evaluation of early-stage product innovation, including GHG sequestration capacity with each m^2 of surface capable to store between 5.5–8.6 kg of CO_2. In addition, the study highlights the importance of modelling irrigation and maintenance scenarios, which represent key drivers of environmental performance, and will be further investigated in future experimental monitoring. The findings offer insights into opportunities for integrating modular NbS into sustainable built environments.

Keywords: Nature-based solutions · Green roofs · Green façade · Climate Change Mitigation · Ecosystem services

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1 Introduction

Environmental damage resulting from construction activities has historically not been fully considered in development decisions, influencing urban policies and planning practices [1]. The increasing and uncontrolled expansion of built and paved areas has globally led to the gradual loss of green spaces in cities [2].

Nowadays, due to risen environmental awareness, various incentive programmes promote Nature-based Solution (NbS) as an alternative solution to traditional grey infrastructures, aimed at regenerating the functionality of natural ecosystems [3]. In particular, NbS applied at the building scale, such as green roofs and green facades, offer multiple benefits, including their contribution to the regulation of rainwater runoff, mitigating the effect of UHI, improving biodiversity, air quality and city aesthetics [4–6]. In addition, they promote the sequestration of atmospheric CO_2 through plant photosynthesis, which captures carbon dioxide from the air and stores it as biomass [7, 8].

Despite many advantages, their adoption remains limited. This is largely due to complex maintenance requirements [9], and the technological complexity and material requirements associated with these systems [10]. To overcome these challenges, an innovative NbS named CAPT-TILE [11] has been developed as an alternative to conventional green roof and green façade systems. The CAPT-TILE system is a modular terracotta tile that enables vegetation growth on building surfaces, including horizontal, pitched, and vertical configurations. This paper proposes a methodological life-cycle framework to support the environmental evaluation of these hybrid systems that operate across regulatory and functional boundaries between clay construction products and vegetative components. Through the real case study application of CAPT-TILE production at the Industrie Cotto Possagno facility in Possagno (Italy), the framework focuses on the definition of system boundaries and life-cycle inventory development. In particular, the study quantifies the GHG sequestration potential associated with vegetation growth and highlights the importance of modelling irrigation and maintenance scenarios during the use stage. In doing so, the study establishes the methodological basis for a future full evaluation of the life-cycle environmental performance of the CAPT-TILE system.

2 The CAPT-TILE System

The CAPT-TILE system, shown in Fig. 1, consists of modular prefabricated terracotta tiles (463 mm × 293 mm) with a total depth of 40 mm, including a 30 mm zeolite-based substrate layer glued to the internal tile surface, and pre-cultivated vegetation on top. Vegetation grows on a thin soil layer with an approximal 10 mm thickness integrated with the zeolite substrate. Since CAPT-TILE green roof and façade systems are intended for commercialization in different climatic contexts across Europe, plant selection is limited to species capable of growing on shallow substrates and therefore varies according to climate conditions. For warmer climates, the CAPT-TILE configuration comprises drought-resistant succulent species (i.e., *Sedum*), whereas for colder climates leguminous species (i.e., *Trifolium repens*) is used. In addition, grasses belonging to the Poaceae family may also be adopted, both as macrothermal (i.e. *Cynodon dactylon L. Pers*) or microthermal (i.e., *Lolium perenne L., Poa Pratensis*) species.

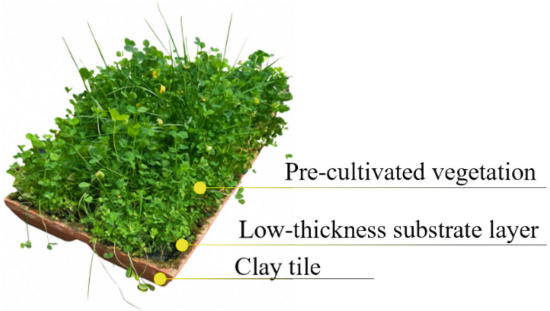


Fig. 1. The single CAPT-TILE tile configuration

The resulting modular tile system can easily replace conventional roofing elements, while enabling vegetation growth on building surfaces.

3 Life Cycle of the CAPT-TILE

In accordance with EN 15804:2012 + A2:2019 [12], the assessment of the life cycle follows the principle of modularity. Under this principle, all processes that influence the environmental profile of the product throughout its life cycle can be assigned to the specific life-cycle module in which they occur. The entire life cycle of a CAPT-TILE is shown in Fig. 2, and it consists of product, construction, use, and end-of-life stages.

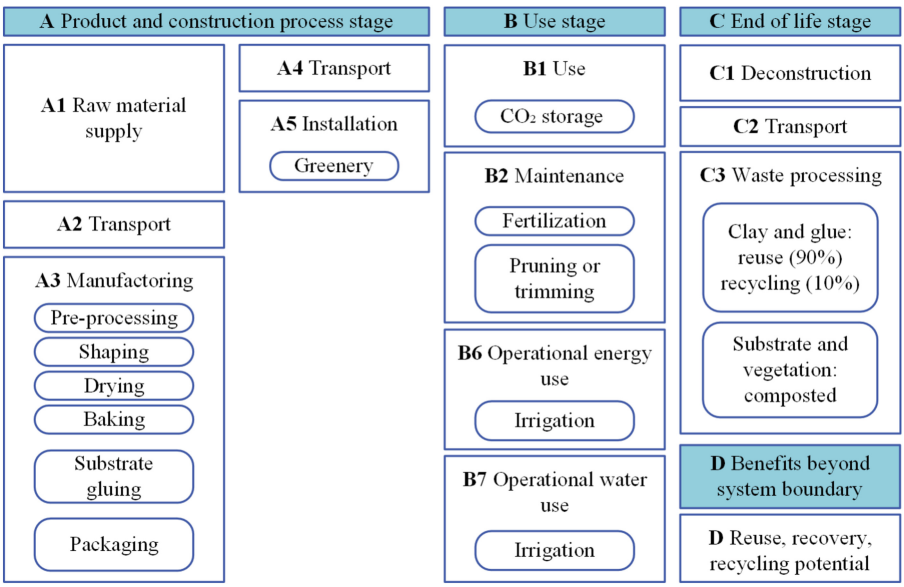


Fig. 2. Life-cycle of the CAPT-TILE

3.1 Product and Construction Process Stage

The product stage includes the processes related to the production of the CAPT-TILE system, from raw material extraction to the manufacturing of the clay tile with the glued zeolite substrate. Module A1 includes the extraction and processing of raw materials required for production. Raw materials used for the manufacture of the CAPT-TILE terracotta tile are clay, water, and mineral additives (i.e., basalt, porphyry limii, barium carbonate). In addition, hydrated lime is used as auxiliary material in the production process. The transport of raw materials and additives to the manufacturing plant (Module A2) is carried out by road using trucks, assuming empty return trips, while handling within the plant is primarily performed using a diesel-powered wheel loader according to the information provided by the manufacturer.

The CAPT-TILE production process can be divided into three stages: terracotta tile manufacturing (see Fig. 3a–d), bonding of the zeolite-based substrate to the tile (see Fig. 3e), and vegetation establishment on the substrate (see Fig. 3f).

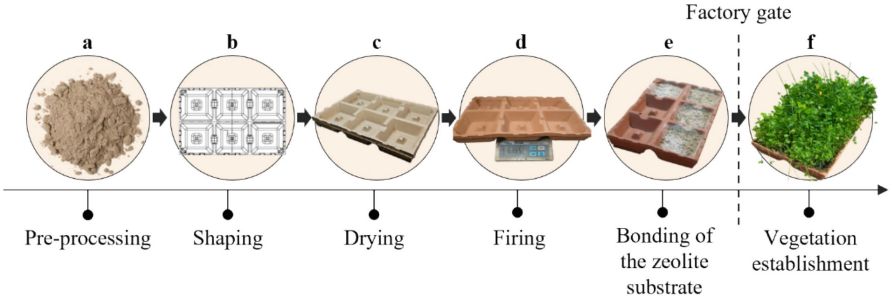


Fig. 3. The CAPT-TILE production process

Primary data concerning the manufacture of the terracotta tile (Module A3), have been directly collected from Industrie Cotto Possagno pilot plant, including the number of raw materials, the machineries, emissions, waste and packaging. The manufacturing plant is powered by electricity (35% from renewable energy sources) and methane supplied from the public energy grid.

The manufacturing process begins with the pre-processing of raw materials. Clay extracted from the quarry is first crushed and mixed with water and specific additives, such as barium carbonate and basalt, to obtain a homogeneous mixture suitable for shaping. In the shaping stage, the mixture of clay paste is pressed into the desired tile geometry. The shaped elements subsequently go through the drying stage, during which the water content is gradually reduced to avoid structural damage during the firing process. During these stages, internal material recovery is implemented: green and dry scraps, generated respectively during pre-processing and drying phase, are collected and reintroduced into the process. Then, the thermal treatment during the firing stage transforms the CAPT-TILE clay body into a durable terracotta product.

At the end of the pilot production line, there are additional machines dedicated to the application of glue (i.e., polyalphaolefin hot-melt adhesive) and zeolite-based substrate layer (i.e., micronized chabazite zeolite of Italian origin). The full formulation

data for these components are not accessible from the suppliers due to confidentiality, thus representative secondary data from recognized databases are used, ensuring technological and geographical representativeness. Instead, the installation of these dedicated machines inside the pilot plant enables detailed accounting of the associated energy consumption for the application and bonding of the zeolite-based substrate layer.

The final vegetative layer of the CAPT-TILE system is installed during the construction stage (Module A5). Vegetated turf rolls grown on commercial soil were supplied by specialized nurseries. During installation, the turf rolls are cut and shaped to match the dimensions of the CAPT-TILE modules and placed over the thin substrate layer integrated into the tile. This process is performed manually and does not require mechanical equipment or additional energy consumption. Data related to the cultivation and harvesting of vegetated turf rolls are obtained from databases, such as Agri-footprint and Ecoinvent, as these processes are considered background processes and do not constitute foreground data within the system boundary.

The CAPT-TILE elements with the glued zeolite-based substrate produced at the manufacturing plant, together with the vegetated turf supplied by the nursery, must be transported to the construction site. Consequently, a specific transport scenario is defined to support the calculation of impacts associated with Module A4. Thus, a reference transport distance of 100 km by road is assumed, using trucks with a payload capacity of 30 tons.

3.2 Use Stage

Conventional clay tiles do not require repair, replacement, refurbishment, or operational energy use during their service life, so Modules B1-B7 can be neglected. This assumption is aligned with the TBE PCR for clay construction products [13] and with common practice in LCA in the ceramic tile industry [14]. However, CAPT-TILEs differ from standard clay products because the system integrates a vegetative layer supported by a thin substrate. The biological components introduce additional processes that fall under specific EN 15804 use-stage modules. Since the use of CAPT-TILE installed on building surfaces is comparable to that of green roofs and green façades, the same processes are considered for the use stage assessment. According to previous LCA studies on these systems, the use phase may include pruning or trimming, irrigation and fertilization activities, and carbon sequestration through vegetation growth [15, 16]. Therefore, the boundaries of the CAPT-TILE system encompass the phases of use (Module B1), maintenance (Module B2), and operational energy and water use (Module B6–7), as reported in the following sections.

CO_2 Capture

The use stage of the CAPT-TILE (Module B1) includes the potential sequestration of atmospheric CO_2 associated with vegetation growth biological processes. To quantify this contribution, the organic carbon content of plant biomass from different CAPT-TILE configurations was experimentally determined under controlled laboratory conditions using the Modified Mebius method [17, 18]. The resulting organic carbon content was multiplied by the initial dry mass of each sample and converted to CO_2 equivalents. As reported in Table 1, the values were normalized to 1 m^2 to estimate the CO_2 storage

capacity [kg CO_2 m^{-2}] associated with the different vegetation–substrate configuration of the CAPT-TILE system.

Table 1. CO_2 storage capacity [kg CO_2 m^{-2}] after laboratory growth, for different CAPT-TILE vegetation configurations.

Vegetation–substrate configuration	CO_2 stored [kg CO_2 m^{-2}]
Mixture of C4 and C3 grass species (Cynodon dactylon, Poa pratensis, Lolium perenne) on commercial soil	5.9
Trifolium repens and Lolium perenne on peat	8.6
Lolium perenne on peat	7.0
Trifolium repens on hydromulch	5.8
Sedum mixture on commercial soil	5.5

Maintenance and Operational Energy and Water Use

Due to the presence of vegetation, the CAPT-TILE system requires periodic maintenance to ensure proper performance. Module B2 includes fertilization activities, based on typical horticultural practices for extensive green systems, while pruning or trimming are considered negligible since operations are manual. In addition, Module B7 includes the water consumption associated with irrigation of the vegetative layer. However, irrigation and fertilization processes are not always explicitly modelled in previous green roofs LCA studies [15]. Therefore, two alternative scenarios (i.e., no-irrigation and irrigation scenario) are considered for the CAPT-TILE system, reflecting the irrigation frequency and seasonal variability to be monitored during a four-year experimental campaign on mock-ups installed under two different climatic conditions foreseen by the project [11]. The irrigation scenario will be defined according to plant water demand through sensors installed for two vegetated applications characterized by different soil moisture requirements (warm-season 30% and cold-season grass species 70%, respectively). Water is supplied primarily from the mains water network through a buffer storage tank, while excess water is recovered and recirculated within the system. In the irrigation scenario, water consumption is accounted for in Module B7, while the associated electricity use for pumps and automated control systems is included in Module B6.

3.3 End of Life Stage

For conventional dry-mounted clay tiles, Module C1 can normally be considered negligible, since tiles can be manually removed without the need for additional energy use [13]. In addition, although CAPT-TILEs incorporate adhesive layers used to bond the substrate and the vegetative system to the clay tile, tests performed by Industrie Cotto Possagno demonstrated that the adhesive can be fragmented together with the tile during dismantling and treated together with the CAPT-TILE clay tile material in subsequent

recycling processes (Module C3). No additional demolition effort required due to bonded materials must be included in Module C1.

At end-of-life, the clay component is assumed to be largely recovered (90%) and reused or recycled, with the remaining 10% sent to recycling facilities, consistent with sector PCRs and typical EoL practice. The vegetative layer and the substrate, both biodegradable, are modelled as composted under Module C3. Finally, the benefits of reuse (90%) and recycling (10%) of clay roof tiles recovered from the demolition site at the end of their life in module C1, and the benefits of recycling and energy recovery of packaging are allocated to module D.

4 Conclusions

This study proposes a methodological framework for the environmental evaluation of innovative modular NbS, serving both as green roof and green façade systems, integrating clay materials and vegetative components. Using the CAPT-TILE system as a case study, the work defines the system boundaries, life-cycle stages, and data collection procedures necessary to assess both the environmental impacts associated with the manufacturing of components and the potential benefits related to vegetation growth on building surfaces, including experimental measurements of plant biomass CO_2 storage. To the best of our knowledge, these measurements represent one of the first attempts to quantify CO_2 exchange at a single green tile-scale. This approach provides novel information to conduct an estimation of the balance between the potential amount of CO_2 removed by the CAPT-TILEs in the operation phase and the amount released in its production and disposal. Considering that ceramic tile production may generate emissions of approximately 14.4 kg CO_2 eq m^{-2} according to literature data [19], the experimental results obtained for CAPT-TILE modules, showing CO_2 storage values of up to 8.6 kg CO_2 m^{-2}, suggest that innovative clay-based NbS may partially offset a significant share of life-cycle emissions. Overall, the proposed framework establishes the methodological basis for a future complete life-cycle environmental assessment of the CAPT-TILE system. In addition, the study highlights the importance of modelling the use stage, including irrigation and maintenance processes which are often simplified or neglected in conventional LCA studies of vegetated systems. Future research will focus on the full quantification of environmental impacts across all life-cycle stages, including the validation of vegetation performance and maintenance scenarios under real building operating conditions.

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Circularity Strategies for End-of-Life Stage of a Multi-storey Wood Building: Climate Change Impact Analysis Using Static and Dynamic Life Cycle Assessment

Ambrose Dodoo[1(✉)], Olubukola Tokede[2], and Jonn Are Myhren[3]

[1] Department of Building Technology, Linnaeus University, 35195 Växjö, Sweden
ambrose.dodoo@lnu.se
[2] School of Architecture and Built Environment, Deakin University, Geelong, Australia
[3] Sustainable Energy Research Centre, Dalarna University, 79188 Falun, Sweden

Abstract. This study assesses the climate impact of a multi-storey wood building in a life cycle perspective, using both static and dynamic life cycle assessment (LCA) approaches. It investigates how different circular economy scenarios encompassing recycling, reuse and cascading use affect the life cycle climate impact of the building. The results show notable differences in the calculated climate impact depending on the LCA approach, highlighting the importance of comprehensive accounting of biogenic carbon. The building's end-of-life stage gives a significant climate benefit when implementing circularity strategies for post-use wood materials. Among the assessed strategies, cascading provides the greatest climate benefit and results in the lowest life cycle climate impact for the building. Relative to the dynamic LCA (at year 100), the static LCA estimated a 138% higher climate impact for the baseline scenario involving energy recovery, and substantially underestimated the benefits of the circularity strategies. For recycling and reuse, the static LCA even showed 9–19% higher climate impacts than the baseline scenario. Overall, the findings demonstrate that both the choice of circularity strategy and the LCA approach substantially influence the calculated life cycle climate impacts of wood-based materials and buildings.

Keywords: Climate Impact · Circular Economy · Dynamic Life Cycle Assessment · Static Life Cycle Assessment · Wood Construction Materials

1 Introduction

The production and use of buildings account for about half of all extracted materials consumption and about one-third of waste generation within the European Union (EU) [1]. Improving material efficiency and promoting circularity across the design, construction, use and end-of-life (EoL) stages of buildings are vital steps toward a resource-efficient and low-carbon society. Alongside the ongoing efforts to improve energy efficiency and decarbonise the built environment, circular economy strategies are suggested as essential for achieving the 1.5 °C climate target of the Paris Agreement [2, 3]. According to

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the Circularity Gap Report [4], measures such as circular construction materials with recycled content and resource-efficient construction need to be implemented by 2050 to support achieving the Paris Agreement climate target. The EU Circular Economy Action Plan aims to advance circular economy in the built environment and among others identified the building and construction sector as a key area for advancing circularity practices [5].

Several Life Cycle Assessment (LCA) studies demonstrate the climate benefits of wood-based construction products and buildings compared with functionally equivalent non-wood alternatives [6–8]. However, most of these LCA studies focus primarily on the production stage of buildings. A comprehensive approach to sustainable construction needs to consider the entire material chains, from raw material extraction to EoL management [9]. Effective management of EoL building materials facilitates circular material flows in the built environment and thereby reduces environmental impacts. Munaro et al. [10] noted opportunities for circularity interventions at the EoL stage through strategies such as life extension, resource recovery, and recycling.

Previous studies (e.g. [11, 12]) explored the environmental implications of alternative pathways for post-use wood building materials, showing that efficient management of such materials can give significant net climate benefits. However, these studies are based on static LCA which does not address the timing of biogenic carbon flows. Dynamic approaches, on the other hand, are more suited for LCA of wood-based systems as such an approach comprehensively addresses the dynamics of biogenic carbon storage, delay and eventual release as emission [13].

This study compares the implications of using static and dynamic LCA approaches for analysis of the climate impact over the life cycle of a multi-storey wood building, focusing on the implications of circular economy practices for post-use wooden building materials, including recycling, reuse and cascading.

2 Methodology

Static and dynamic LCA methodologies are used to analyse the climate impact of a cross-laminated timber (CLT) building and to explore how different circularity strategies for the post-use wooden materials affect the building's life cycle climate impact.

2.1 Case Study

The CLT multi-storey building for the study was constructed in 2015 in Växjö, Sweden, and comprises 39 apartments with a total heated floor area of 2780 m^2. A photograph of the building is shown in Fig. 1. The mass of materials comprising the building is presented in Table 1. CLT is used for the building's exterior and interior walls, as well as for the intermediate floors. CLT, together with other wooden materials in the building, represents about one-fifth of the building material mass. Aggregates dominate the mass of materials and is used in the foundation and intermediate CLT floor slabs for stability. The other wooden materials (in Table 1) comprise plywood, glued laminated timber, chipboard, laminated wood flooring, wood decking, and wood used as laths and for doors. The other



Fig. 1. Photograph of the studied CLT building in Växjö, Sweden.

non-wood materials include asphalt, cellular plastic, cement, aluminium, polyethylene, and polypropylene.

Table 1. Material mass balance of the studied CLT building.

Material	Mass (tonne)	Material	Mass (tonne)
Aggregates	1091.8	Insulation (mineral wool)	53.7
Concrete	929.7	Coarse concrete	36.5
CLT	443.2	Rebars (recycled steel)	24.8
Gypsum board	225	Window	20.4
Other wooden materials	175.8	Facade stones	19.6
Steel (connections)	84.4	Glass	19.6
Plaster putty	79.6	Other non-wood materials	15.8

2.2 Scope of the Study

Functional Unit and System Boundary: The climate impact of the complete building is analysed over a 50-year reference service life, and normalised to 1 m^2 building floor area to compare the implications of the different circularity options and LCA approaches. The system boundary of the analysis follows EN 15978 [14] and EN 15804 [15], and is defined to include all activities connected to the product and construction (A1-A5), use (B1, B2 and B4) and EoL (C1-C4) stages and the potential benefits and burdens from post-use building material recovery and management (D).

2.3 Inventory Analysis

Product and Construction Stages: The inventory in the product stage (A1-A3) includes emissions of CO_2, CH_4, and N_2O from fossil fuels and cement production processes and biogenic carbon flows. These are calculated based on the mass of materials in

the building, using life cycle inventory datasets for material processing, energy supply, and transport from the Ecoinvent database (v3.8) [16]. The biogenic carbon flows associated with wood-based materials are accounted for using the −1/+1 approach. During the construction stage (A4-A5), emissions from transport are calculated using specific transportation emissions data from Ecoinvent (v3.8), while those for the construction and installation processes are calculated using standard data for the Swedish conditions [13]. Details of the modelling data are given in Dodoo et al. [13].

Use Stage: Carbon uptake associated with concrete carbonation (B1), maintenance (B2) and replacement (B4) are included in this stage. The carbon dynamics of carbonation are calculated using data provided by Dodoo et al. [17] while the emissions associated with B2 and B4 are calculated using data from Ecoinvent (v3.8) [16].

EoL and beyond Stage: The building is assumed to be deconstructed through selective dismantling after a 50-year reference service life. This is followed by the transport and reprocessing of EoL building materials, with a focus on wooden products, particularly the CLT panels as the main structural building material. The emissions accounted for at the EoL stage comprise those associated with the building's deconstruction (C1), the transport of post-use materials (C2), material processing (C3), and the potential environmental benefits (D) associated with the post-use material recovery and management. Following Dodoo et al. [17], 90% of the wood, concrete, steel, aluminium, and glass comprising the building are assumed to be recovered for further reprocessing. For concrete, steel, aluminium, and glass, recycling is assumed. The wooden materials are assumed to be recovered for energy in the baseline scenario, displacing fuels used for district heating, and are compared with circular economy strategies, including recycling, reuse, and cascading. Emissions from the EoL and beyond stages are calculated using data from Ecoinvent (v3.8) [16], supplemented with data from [18]. Transport-related emissions are calculated assuming the use of Euro 3 trucks and a distance of 100 km to waste processing sites.

Circularity Strategies: The circularity strategies explored (Table 2) mainly target the CLT as the structural building material, and aim to extend material use and delay biogenic carbon release. The recycling scenario assumes reprocessing of the CLT panels into wood chips for particleboard production. The reuse scenario assumes the use of the CLT panels in new applications while the cascading use follows a hierarchy where the CLT panels are first reused, then recycled into particleboard chips, and finally used for energy recovery. The substitution benefits from the post-use materials are allocated to the studied building after the end of its service life (year 50).

Table 2. Circularity scenarios and assumptions for CLT and other materials.

Scenario	Description
Recycling	90% of CLT/other wood recycled; 90% of other materials (see texts) recycled
Reuse	70% of CLT/other wood reused & 20% recycled; 90% of other materials recycled
Cascading	Reuse (as above) first, then recycling, and finally energy recovery of all wood.

2.4 Impact Assessment

Static and dynamic modelling approaches detailed by Dodoo et al. [13] are used for the impact assessment. The static approach uses Global Warming Potential (GWP-100) factors to convert the total emissions of each greenhouse gas (GHG) into CO_2-equivalent values using characterisation factors of 1, 29.8 and 273 for CO_2, CH_4, and N_2O, respectively, from the IPCC [19]. The dynamic approach accounts for the temporal distribution of GHG emissions and removals by tracking their annual flows and calculating climate effects over time using atmospheric response functions and radiative forcing models.

3 Results

Figure 2 presents the life cycle climate impact of the building for the recycling scenario, while Table 3 summarises the climate impacts for all the circularity scenarios and baseline of energy recovery, all calculated using the static LCA approach. In Table 3, the value for the production stage is negative because it includes the biogenic carbon storage (in Fig. 2), which is 1.3 times greater than the fossil carbon emissions. The impacts of the production stage and the use stage are the same for all scenarios and the baseline, as the differences between them arise from the EoL options, which vary across the cases. Overall, cascading provides the greatest benefit and results in the lowest climate impact. In contrast, reuse and recycling show 9% and 19% higher climate impacts than the baseline, respectively, according to the static LCA.

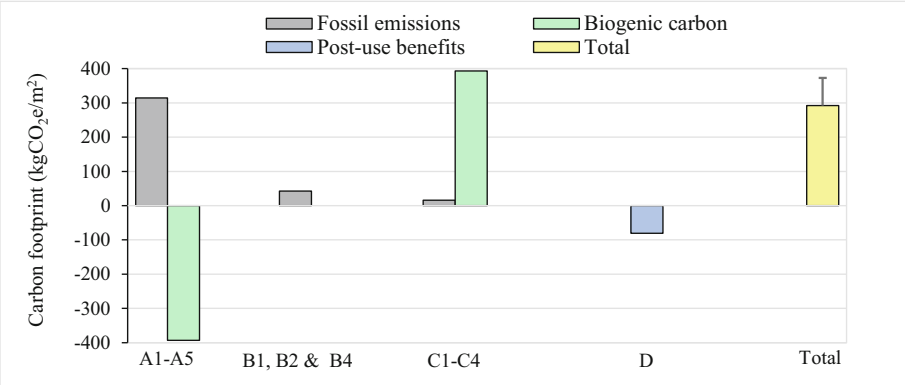


Fig. 2. Climate impact over the life cycle of the building. For the total, the main bar shows when including post-use benefits (D) and the error bar shows values excluding these benefits.

Table 3. Life cycle climate impact of the building under alternative EoL options (static LCA).

Life cycle stages	Climate impact (kg CO_2e/m^2) with alternative EoL options for CLT			
Production (A1-A5)	−99			
Use (B1, B2, & B4)	42			
EoL & beyond (C1-C4, D)	*Baseline*	*Recycling*	*Reuse*	*Cascading*
	302	348	324	266
Balance (net total)	**245**	**291**	**267**	**209**

Figure 3 shows the life cycle climate impacts of the building when the calculation is based on dynamic LCA. Essentially, the estimated climate impact varies with the time window over which the cumulative effects of GHG emissions and removals are assessed. Concrete carbonation during the building's service life (module B1) caused the gradual downward trend in the figure due to slow carbon uptake over time. Table 4 summarises the building's climate impacts for the dynamic LCA at year 100 and year 200 and also the life cycle climate impacts of the static LCA (based on Table 3). It shows differences in both the ranking and magnitude of the options between the dynamic and static LCA. The dynamic LCA shows that cascading gives the lowest climate impact, followed by reuse and recycling, with the baseline providing the least climate benefit and therefore the largest climate impact. This contrasts with the results of the static LCA, which ranks the baseline next after cascading. Furthermore, compared with the static LCA, the dynamic LCA shows significantly lower climate impacts and therefore greater benefits for the circularity strategies. This difference is due to how biogenic carbon is accounted and treated under the two assessment approaches. In contrast to the baseline, all the circular economy scenarios show negative climate impacts at year 100, indicating a cooling effect and thus substantial climate benefits. However, at year 200 only the cascading scenario shows a negative climate impact, although the climate impacts of recycling and reuse remain lower, between 31–42% lower than the baseline of energy recovery.

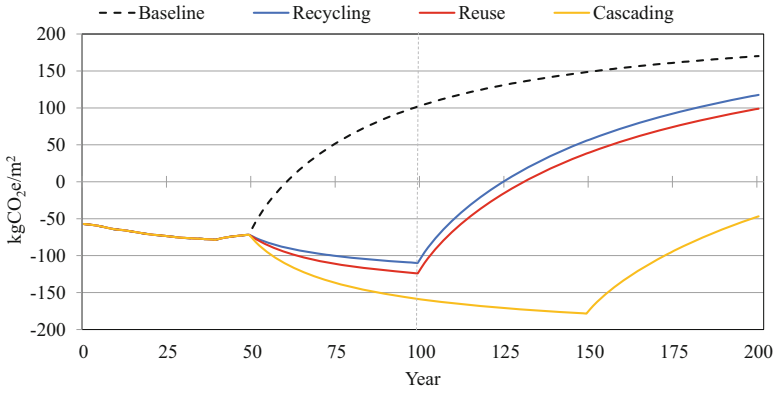


Fig. 3. Life cycle climate impact of the building under alternative EoL options (dynamic LCA).

Table 4. Climate impact of the building under alternative EoL options when using dynamic and static LCA approaches.

Description	Climate impact (kg CO_2e/m^2)		
	Dynamic LCA at year 100	Dynamic LCA at year 200	Static LCA (GWP-100)
Baseline	103	170	245
Recycling	−102	118	291
Reuse	−117	99	267
Cascading	−159	−47	209

4 Discussions and Conclusion

This study shows that the explored circularity strategies, encompassing reuse, recycling, and cascading, give significant climate benefits, and the choice of EoL strategy has a significant influence on the building's life cycle climate impact. It also demonstrates the relevance of the LCA approaches for analysing circularity strategies in wood-based systems. While several LCA studies have explored climate change implications of circularity strategies for the EoL of wood building materials, most are based on static LCA, and there is a paucity of studies using dynamic LCA approach. The present study therefore contributes to the literature by examining the implications of applying both static and dynamic LCA approaches in such a context.

The findings show significant differences in both the magnitude and ranking of climate impacts when using the static and dynamic LCA approaches. Cascading consistently provides the lowest climate impact across all approaches. The dynamic LCA showed much lower impacts, reflecting the benefits and effects of temporal carbon storage in wood-based materials. This also changed the relative performance of the EoL strategies explored compared with the static LCA. Reuse and recycling showed lower impacts than the baseline in the dynamic LCA, while in the static LCA both strategies resulted in 9–19% higher climate impacts than the baseline scenario.

These findings highlight the importance of accounting for the temporal dynamics of GHG flows in LCA of wood-based systems. They also add to growing evidence (e.g. [13, 20]) that dynamic LCA provides a more robust approach to treating biogenic carbon in wood-building LCAs. For example, Mghazli et al. [20] reported that static LCA yields 50% higher climate impacts for a wood building than dynamic LCA over a 50-year time horizon. Similarly, the present study showed that, compared with the dynamic LCA at year 100, static LCA gave a 138% higher climate impact for the baseline scenario. At year 100, the dynamic LCA showed reductions in climate impacts of 199%, 214%, and 254% for recycling, reuse, and cascading, respectively, compared with the baseline. In contrast, the static LCA indicated increases in climate impacts of 19% for recycling and 9% for reuse, and only a 15% reduction for cascading compared with the baseline, thereby substantially underestimating the climate benefits of circularity strategies.

Despite the potential benefits, several barriers limit the implementation of circularity strategies in the building sector. For example, buildings are often not designed to facilitate

post-use material recovery [21, 22]. To realise the climate benefits identified in this study, greater emphasis should be placed on design and construction practices that facilitate material recovery at the building's EoL. Overall, this study demonstrates the relevance of the choice of EoL strategy and the assessment approach, as both have a significant influence on the overall climate performance of a building.

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Relative Indicators and Reference Benchmarks for Environmental Assessment of Buildings

Roman Rabenseifer(✉), Katarína Minarovičová, and Katarína Červeňová

Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Bratislava, Slovakia
roman.rabenseifer@stuba.sk

Abstract. The increasingly urgent need to reduce greenhouse gas emissions and the ambition to achieve carbon neutrality by 2050 have intensified the necessity for EU member states to implement comprehensive evaluations of environmental impacts, including in the building construction sector. Today, we are approaching the limits of what can be achieved through further reductions in operational energy consumption of buildings. However, there is still significant potential for reducing building's primary embodied energy demand, which simultaneously offers opportunities for lowering greenhouse gas emissions expressed in terms of global warming potential (GWP). In this article, in addition to evaluating the current state of establishing GWP threshold values for building's embodied energy across EU countries, we also propose the development of reference benchmarks expressed per unit of heated floor area. In generating these benchmarks, we account for the building shape factor (the ratio of the heat exchange area of the building's envelope to the heated volume of the building), which is also used in the assessment of operational energy performance of buildings - and distinguish between two categories of envelope systems: heavy-mass and lightweight. We further present simplified examples demonstrating that relative indicators (e.g., GWP per m^2 of heated floor area) related to the shape factor provide a more accurate picture of actual environmental performance compared to values expressed only in relation to the unit of building's heated floor area.

Keywords: Embodied Energy · Global Warming Potential · Shape Factor · Benchmarking · Life Cycle Assessment · EPBD IV

1 Introduction

European climate policy as shaped by the Green Deal [1], the Climate Law [2], and successive revisions of the Energy Performance of Buildings Directive (EPBD) has driven new buildings toward ultra-low-energy or near-zero-energy performance. As operational energy demand approaches its practical minimum, attention is shifting toward embodied impacts arising before a building is commissioned.

Despite their importance, embodied impacts remain insufficiently regulated. Voluntary schemes such as BREEAM [3], LEED [4], and DGNB [5] include indicators

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for primary energy input (PEI) and global warming potential (GWP), but their benchmarks vary widely. EPBD IV [6] marks a turning point: from 2028, new buildings above 1000 m^2 must report their whole-life GWP, with the requirement extending to all new buildings from 2030.

Several EU Member States have already introduced embodied carbon limits (Fig. 1). However, the methodologies used to derive these limits differ significantly. A comparative review of available approaches showed that the reliability of benchmark values depends primarily on the representativeness of input data rather than on building typology or software.

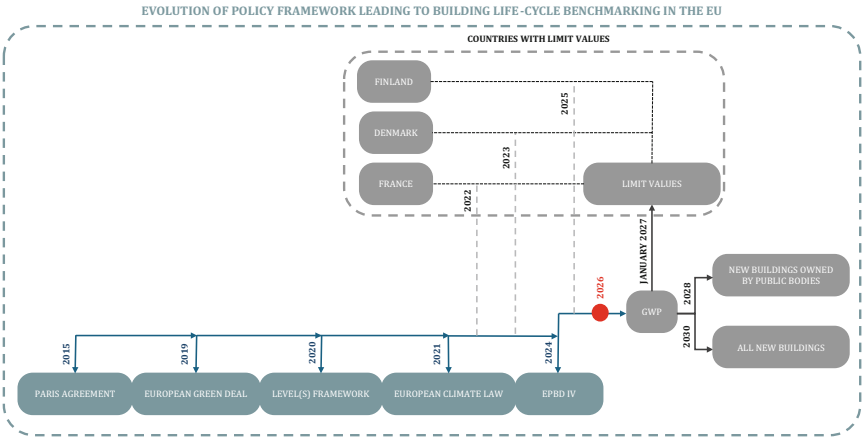


Fig. 1. Evolution of embodied carbon benchmarking in Europe (the list of countries with limit value is indicative only).

A more fundamental challenge concerns the indicators themselves. Absolute values favour small buildings; per-square-meter values ignore geometric efficiency. The authors' previous work [7, 8] suggests that the building shape factor (the ratio of the heat exchange area of the building's envelope to the heated volume of the building - *A/V* ratio), long used in operational energy assessment, provides a fairer basis for comparing embodied impacts.

This paper has three objectives:

- summarize recent European methodologies for establishing reference values;
- demonstrate why geometry-sensitive indicators are needed;
- propose a geometry-based benchmarking framework compatible with EPBD IV.

2 Current Approaches to Establishing Carbon Footprint Reference Values

The development of national benchmarks for embodied carbon has accelerated across Europe in response to the requirements of EPBD IV and the broader climate neutrality agenda. However, the methodological diversity among Member States remains substantial. Below are summarized four representative approaches. These approaches differ in data sources, system boundaries, statistical treatment, and intended regulatory application.

2.1 Parametric Modelling (Hungary) [9]

A parametric approach generates thousands of hypothetical residential buildings by varying key geometric parameters. Embodied carbon is calculated for modules A1–A3, B4, and C3–C4 of building's life cycle assessment. Reference values are expressed as median and percentile ranges (9.1–15.5 kg CO_2-eq/m^2/year). This method is useful where real LCA data are scarce, though it lacks real-world validation.

2.2 National Methodology Based on Real Projects (Czech Republic) [10]

The Czech INDICATE project assessed 50 most common types of real buildings (e.g., single-family houses, multi-residential buildings, office buildings, educational facilities, and logistic halls) using harmonized bills of quantities and BIM models. The full life cycle (A–C) was evaluated under three operational energy scenarios. The approach is accurate and representative but limited by sample size and incomplete national EPD coverage.

2.3 Pilot Study of Office Buildings (Poland) [11]

A preliminary benchmark of ~5000 kg CO_2-eq/m^2 over 60 years was derived from 11 office buildings. While useful as a first step, the dataset is too small and not fully harmonized with EN 15978 [12].

2.4 Analytical Basis for National Limit Values (Denmark) [13]

Denmark's methodology is the most comprehensive. From 163 representative buildings, a national limit value was defined as the 66^{th} percentile of area-weighted GWP results, yielding 9.9 kg CO_2-eq/m^2/year (A1–A4, B4, B6, C3–C4). Typology-specific limits were also introduced. Limitations include underrepresentation of some building types and mixed data sources.

2.5 Synthesis

Across all reviewed methodologies, a consistent pattern emerges: the reliability of benchmark values depends primarily on the representativeness and quality of input data, not on building typology or LCA software.

Countries with limited datasets may rely on parametric modelling, while those with established digital workflows can develop harmonized national databases. However, none of the reviewed methodologies explicitly address the influence of building geometry on embodied impacts - a gap that motivates the next section.

3 Limitations of Absolute and Per-Square-Meter Indicators

Absolute embodied energy or GWP values scale with building size and therefore favour small buildings. Normalizing by floor area improves comparability but still ignores geometric efficiency. Two buildings with identical floor areas may differ significantly in envelope area, proportions, or number of storeys, leading to large differences in embodied impacts.

The shape factor (A/V ratio) captures the relationship between envelope area and heated volume. It governs both heat transfer (operational energy) and material quantities (embodied impacts). Indicators that ignore this relationship risk unfairly penalizing certain typologies and distorting design incentives.

4 Geometry-Based Assessment of Embodied Impacts

4.1 Influence of Shape Factor

In the study published in Energies (2025) [7], a set of simplified geometric variants was generated by scaling a $3 \times 3 \times 3$ m cube in one or more dimensions. For each variant, the envelope area, heated volume, and shape factor were calculated, and embodied impacts were assessed for the product stage (A1–A3) using ÖKOBAUDAT data [14]. The results revealed two key relationships:

- Absolute embodied energy and GWP decrease with increasing shape factor (smaller buildings require fewer materials in total).
- Embodied energy and GWP per square meter increase with increasing shape factor (compact multi-storey buildings use materials more efficiently per unit of heated floor area).

These findings demonstrate that the shape factor governs the efficiency of material use in a similar way it governs heat transfer in operational energy assessments (Fig. 2)

4.2 High-Mass vs. Lightweight Systems

Using identical geometries, lightweight timber-based variants exhibited substantially lower embodied impacts than high-mass reinforced-concrete variants (Fig. 2). This supports the need for separate benchmark categories.

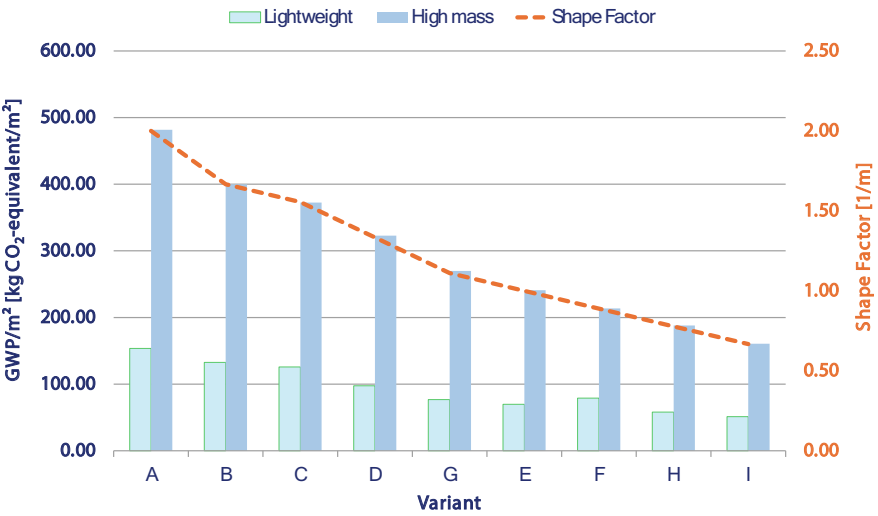


Fig. 2. Relationship between shape factor and GWP/m^2 - comparison of high-mass and lightweight variants. The shape factor (dashed line) is linked to the secondary y-axis and the GWP/m^2 value to the primary y-axis (adapted and redrawn from [7]). The letters A through I denote geometric variants ranging from 3 × 3 × 3 m to 9 × 9 × 9 m.

4.3 Influence of Floor Area, Proportions, and Roof Geometry

A later study (Energies, 2025 [8]) analyzed 40 realistic family house variants. Results showed that:

- multi-storey buildings have significantly lower embodied impacts per square meter;
- elongated floor plans increase the shape factor and embodied impacts;
- roof geometry has a secondary but noticeable effect.

4.4 Theoretical Basis

The Energies studies [7, 8] provided a theoretical justification for using the shape factor in embodied impact assessment. Since the same geometric parameters govern both operational and embodied performance, the shape factor offers a natural bridge between the two.

5 Proposal for a Geometry-Based Benchmarking Framework

The framework is based on fairness, representativeness, transparency, scalability, and compatibility with EN 15978 [12], EN 15804 [15] and EPBD IV [6].

5.1 Geometry-Adjusted Indicator

A geometry-adjusted benchmark metric, in this case for GWP_{adj}, is proposed:

$$GWP_{adj} = \frac{GWP_{A1-A3}}{A_{HF}} \times f(F_b) \tag{1}$$

where f_b = a/v ratio, i.e., the shape factor, $f(f_b)$ adjusts the benchmark to account for geometric effects, A_{HF} stands for heated floor area and $GWP_{A1\text{-}A3}$ for the embodied GWP of the product stage of the life cycle assessment. Compact buildings (low f_b) can meet stricter thresholds due to their efficient use of materials, while less compact buildings (high f_b) receive geometry-adjusted limits that ensure fair comparison.

5.2 Separate Categories

Given the large differences between high-mass and lightweight systems, two benchmark categories are proposed. Each category would have its own benchmark curve $f(f_b)$, reflecting typical material intensities for either system.

5.3 Data Collection Through Permitting and Certification

Embodied impact calculations can be integrated into building permitting and energy certification. This distributes data generation across the sector and avoids large-scale stock surveys. A transitional period can be used to collect data before applying thresholds.

The approach aligns with the gradual introduction of embodied carbon limits across Europe (Fig. 1) and offers a more nuanced alternative to fixed per-square-metre thresholds.

6 Conclusions

The move toward whole-life carbon assessment requires benchmarks that reflect real material efficiency rather than arbitrary typological differences. Existing European methodologies provide valuable insights but do not fully address the influence of geometry.

The authors' previous studies show that the shape factor (*A/V* ratio) is a strong predictor of embodied impacts and can serve as a fair basis for benchmarking when combined with heated floor area (A_{HF}) normalization. Distinguishing between high-mass and lightweight systems further improves accuracy.

Integrating embodied impact calculations into permitting and certification processes offers a practical way to collect representative datasets. Once sufficient data are available, geometry-adjusted benchmark curves can be calibrated and progressively tightened.

Refinement and practical implementation of this approach will benefit from ongoing research, real-world testing, and shared experience among different countries.

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Ecosystem Services and Life Cycle Impact Assessment of Building Materials: A Scoping Review

Marina da Silva Seabra da Rocha(✉) and Eleonora de Sad de Assis

Architecture School, of Federal University of Minas Gerais, Paraíba Street, 697, 30130-141 Belo Horizonte, MG, Brazil
marinasseabra@gmail.com

Abstract. Life Cycle Assessment (LCA) is one of the most widely used methods for assessing construction sustainability. Despite its widespread adoption and well-established nature among assessors and certifiers, it faces some limitations. Therefore, the ecosystem services (ES) approach appears to be a promising alternative for overcoming these barriers. However, its theoretical basis remains underexplored as a complement to the LCA of building materials. Thus, this investigation, conducted through a scoping literature review, aims to identify the strengths and limitations of LCA-driven methods that incorporate ES principles for assessing the environmental impacts of building materials. We conclude that there are four types of LCA driving methods, with varying degrees of ES integration. However, ES integration into LCA for construction materials remains insufficient, as existing methods exhibit several limitations. This investigation contributes to identifying barriers and pathways for achieving true circularity in the built environment. It highlights the necessity of developing a new sustainability assessment tool that integrates ES on LCA, creating a unique assessment metric for the impacts of construction materials on ES, guiding built environment professionals in material selection, and potentially serving as a certification system.

Keywords: LCA · Building Materials · Construction Materials · Ecosystem Services · Scoping Review

1 Introduction

In the words of Vanderwilde and Newell [1] and Vieira, Calmon and Coelho [2] LCA is the main instrument for environmental management, as enshrined in the ISO 14.040 series of international [3] and ISO 14.044 [4] and the national technical standards. It is an "internationalised and standardised process for assessing the environmental impacts of products or processes throughout their life cycle" [1]. It is also one of the most explored in recent literature when compared to other assessment tools [2].

However, LCA is a very complex, expensive and subjective method [5], concerning the choice made by the assessor of boundaries of the product or process system being analysed, the objectives and even the scope of the assessment. In addition, it can be very

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time-consuming, requiring a lot of experience of the person carrying it out and a large set of data that is often unavailable or non-existent [6]. And it also does not have indicators that are easily understood or aggregated into a single metric unit [7]. This method is not capable of fully accounting for impacts on the provision of ecosystem services – ES. LCA focuses above all on the interference of its object of study on regulation and maintenance services, especially carbon emissions. Despite this discrepancy between the two frameworks, LCA and the ES approach share environmental sustainability objectives [1].

Consequently, the aim of this study was to conduct an scoping review (ScR) and raise the potential and limitations of the traditional types of LCA that are used to assess the impacts of construction materials on the environment with LCA's that are based on the precepts of ecosystem theory, to assess these same impacts.

This review is justified by the need to provide an up-to-date overview of research published on the subject, which is still in its beginnings, and to outline the current debate on the subject. Likewise, the relevance of this research is evident since there are no recent reviews that have targeted the survey proposed in this investigation. Furthermore, the aim is to demonstrate that the LCA approach, as it is currently applied, is limited, concerning its understanding of impacts on ecosystem. And finally, by providing a compilation of the characteristics of existing methods, this research contributes to make a conscious choice about the type of LCA that should be adopted in assessment situation.

2 Materials and Methods

The research used the scoping review technique using Parsifal to conduct it. The publications searched were limited to the time interval 2003 to 2023. The initial year chosen as a milestone was due to the fact that it was the year in which the Millennium Ecosystem Assessment was published [8], a scientific reference for the approach to the theory of ecosystem services. Searches for open-access publications were conducted in the ScienceDirect database, which hosts a substantial number of journals and studies in the environmental field, as indicated in prior research. This approach was adopted because, in addition to the fact that ScR can serve as a preliminary step for future in-depth investigations, it is also possible to adapt the method to resource constraints by developing a robust search string and limiting the investigation to a single database [9]. The review followed the PCC framework, and the search string used was: ("construction material" OR "building material") AND ("life cycle assessment" OR LCA OR "life cycle") AND "assessment" AND ("ecosystem services").

As shown in Table 1, the initial number of publications found was 188, which were exported to BibTex file that was uploaded to Parsifal. Two duplicates were eliminated and then a first selection was made manually. It was verified if the study focused on buildings, building materials and life cycle assessment or ecosystem services. 84 documents remained at the end of this initial filtering.

On the other hand, research that dealt with Building Information Modelling – BIM –, other sustainability assessments, water supply and sewage systems, energy systems (fuels and other sources), LCA of aquaculture, forests, plantations, aquatic or terrestrial biomes, algae, studies on materials or construction elements that did not deal with LCA or

Table 1. Steps of Scoping Review.

Step	Number of documents
Initial sample	188
Practical screening	84
In depth screening	16
Final Sample	12

ecosystem services, other environmental studies (e.g. environmental impact assessment – EIA, climate study, performance of materials and building elements, remediation, state of the art on new technologies, pollution, environmental risks and artificial reefs), research focused on policies and the role of stakeholders, as well as other LCA studies that did not deal with buildings or building materials and congress proceedings, were discarded. 16 texts advanced to the next stage, as shown in Table 1. The 16 publications were saved in a folder in the Mendeley software and submitted to a second filter based on content compatibility assessment. In total, 12 studies were selected to make up the *corpus*. Therefore, 10 articles and two book chapters remained to make up the textual basis for data extraction.

The purpose of the data extraction, using Parsifal, was to map: The occurrence of the expression "ecosystem services" in different parts of the text; Whether the focus of the research was on buildings, materials or entire urban areas; What the target material of the study was, when relevant; Which phases of the object's life cycle were assessed; Which types of traditional LCA or ecosystem-based methods were presented; Which potentialities and limitations of these procedures were listed and the name of the new method, if proposed. At the end of this process, a .csv file was exported and opened in Microsoft Excel. The information collected was reviewed, then completed in there were missing passages, and finally summarised.

3 Results

It is important to emphasise that only half of the 29 methods mapped are discussed in terms of their advantages and limitations. The methods listed were divided into four classes: LCA methods, economic methods, ecosystem methods, and energy analyses, as seen in Table 2.

3.1 LCA

There are eight LCA methods mentioned. However, only traditional LCA and the Life Cycle Model of Carbon Emissions for Urban Building Systems - LCCE Model - were explored. LCA assesses the main types of impacts, such as global warming, acidification and eutrophication, at different spatial scales, in addition to the embodied energy [10, 11]. Azari [10] also mentions that it is a solid and well-established quantitative methodology that can be used for comparing materials, elements and buildings. Besides, Li and Wang

Table 2. Main strengths and limitations of each method class.

Strenghts	LCA	Economic	Energy	Ecosystem
Complete and well-established LC assessment	X			
Specific to construction sector	X	X		
Easy comparison			X	
Multi-sector impact assessment	X	X		
Link BE to nature			X	X
Easy cost-benefit analysis		X	X	X
Limitations	LCA	Economic	Energy	Ecosystem
High /local data requirements and complexity	X		X	X
Subjectivity and uncertainties	X	X	X	
Converting unit issues	X	X		
Focus on specific life cycle stages or impacts	X	X	X	
Quantification of non-commercial services		X		
No social aspects considered	X	X		
Market-based models' dependency		X		
Complexity in system boundary definition	X		X	X

[11] state that it is a product-oriented method, in which the environmental effect of the life cycle belongs to the downstream impact indicators.

On the other hand, there are many limitations. Izaola and Akizu-Gardoki [12] affirm that LCA is still very much focused on assessing global warming potential. This method makes difficult to compare its results with the ones from other studies, due to the different metrics and approaches used. Yi, Srinivasan and Braham [13] and Yi et al. [14] explain that in conventional and recent approaches, accounting for the impacts of the building's life cycle does not include the environmental formation phase of renewable and non-renewable resources. In general, these approaches ignore the direct link between the built environment (BE), and the larger geobiological system. In other words, the contribution of energies, including solar, wind and other renewable and non-renewable resources and ecosystem services to the formation of raw materials, geobiophysical materials and human or social services are not calculated as inputs.

As stated by Azari [10] and Cao et al. [15], LCA can induce subjectivity, whether in determining the weight of each impact, in the objectives and definitions and assumptions of the LCA. In addition, they can provide incomplete information and uncertainties due to lack of knowledge and data from regional and local bases on the environmental contribution to the social economy of that process. Furthermore, Azari [10] emphasizes that uncertainties are inherent to the LCA process. They result from a lack of knowledge about the functioning of the system under study or the inaccuracy of a model in representing the physical system, measurement errors caused by small sample sizes used in data collection or errors in data collection. Furthermore, according to Azari [10], LCA

is a modeling tool that is not very friendly to architects to utilize during the early stages of design analysis.

Finally, as stated by Yi, Srinivasan and Braham [13], LCA is based on temporal and spatial scales of impacts and processes corresponding mainly to initial production phases. Like EmA, it does not take into account the energy incorporated into the material formation process. And this can limit the window in which this method can be employed. The authors also pointed out that among the index related to energy accounting in LCA, few provide information that can be summarized in a single unit. While Srinivasan et al. [16] conclude that traditional LCA does not fully account for impacts on the provision of ecosystem services.

3.2 Economic Methods

There are three methods covered is this category: Economic Input-Output based method of LCA - IOE-LCA Cost Benefit Analysis and Economic Analysis - EA. For the latter two, no advantages are added and Srinivasan et al. [16] say that Cost-Benefit Analysis is an example of a reductionist tool, which evaluates performance by reducing a complex system to a smaller set of variables, integrating only its measurable characteristics. Cao et al. [15], state that EA ignores the impact of the production process on the environment and the environmental contribution to the social economy, meaning that environmental costs can be underestimated.

Azari [10] and Srinivasan et al. [16] state that IOE-LCA is tool that is more comprehensive and specific to the construction sector. It makes possible to compare products and components from different sectors. However, it carries the same LCA uncertainties. Besides, this procedure is based on average US data from more than 20 years ago, which leads to inaccuracies and a mismatch in the results with the present day.

3.3 Energy Analysis

With regard to energy analyses, six sub-methods are discussed: exergy analysis, extended exergy analysis, embodied energy analysis for buildings, emergy or emergy analysis - EmA -, modified or improved emergy analysis and emergy analysis for buildings.

In relation to exergy analysis and expanded exergy analysis, Yi, Srinivasan and Braham [13] state that in the first case, the link between the built environment and many of the larger geobiological systems, including solar, wind, other renewable and non-renewable resources and ecosystem services, is generally ignored. Furthermore, the no-extended method only refers to the current state of energy available for use. These authors make the same complaint about the method that analyses embodied energy for buildings. They also state that in this method the energy demands are calculated only from the extraction of the material, ignoring the environmental loads in the process of forming the input in nature, which is corroborated by Yi et al. [16]. Finally, they add that this procedure does not account for the energy of human labour and supporting services.

Concerning the Emergy method or Emergy Analysis - EmA - Song, Lin and Wu [17] state that the unit of energy per mass is suitable for assessing the recyclability of building materials, obtaining what can be called a total ecological cost. In this way, it is possible to quantify the real-life cycle cost of material production, taking into account

the losses both to the ecosystem and people due to CO2 emissions. Li and Wang [11] emphasise the ability of this method to assess benefits and costs together.

In addition, Yi, Srinivasan and Braham [13], Yi et al. [18] and Srinivasan et al. [15] state reaffirm the holistic nature of this approach, which can analyse systems of different types and scales and human communities with a common indicator, the emergy. It provides synthetic information, facilitating the comparative assessment of energy in the overall contextual energy flow and allowing for an easier comparison of much broader environmental effects. Yi et al. [18], also argue that emergy analysis has an ecological understanding that allows buildings to be conceptualised as locally designed ecosystems, i.e. part of the micro-geobiosphere, incorporating them into the dynamic energy demand of the global environment. Furthermore, according to Yi et al. [14] and Srinivasan et al. [16], this method also assesses the quality, hierarchy and direction of energy flow (from high quality to low quality) for all human services and products.

Regarding the limitations of the emergence technique, Cao et al. [15], Li and Wang [11] and Yi, Srinivasan and Braham [13] state that the impact of emissions of environmental pollutants, such as SO2 and NOx, and acidification, and the waste discarded from the transformation process are often ignored in studies because the relevant emergy accounting ends after the product or service has been generated. This is because Emergy Theory is derived from natural ecosystems, and there is no waste in natural ecosystems. The authors also criticise this method because of the strange generalisation of transformation values, its uncertainty in the synthesis process and its unstable definition of the global energy baseline. Finally, another weakness pointed out by Cao et al. [15] is that in classical EmA all purchased inputs are considered to be non-renewable ones.

Concerning the modified or improved Emergy Analysis, Cao et al. [15] claim that, as an advantage, this method distinguishes between inputs acquired from renewable sources and inputs acquired from non-renewable sources, surpassing the traditional EmA in this aspect. EmA also distinguishes the quality differences of a variety of resources compared to other methods.

However, as pointed out by Cao et al. [15], modified EMA lacks information related to the system under study. Therefore, it is necessary to improve the value databases, which should cover the main industries in various regions.

The last method derived from emergetic analysis is the Building Emergy Analysis - BEmA. Yi et al. [18] emphasise that the environmental information obtained by this method identifies the building's environmental metabolic performance. And Yi et al. [14] report that it accounts for the environmental performance of a building in a macroscopic view, thus allowing it to be compared with other environmental systems, being useful in Net-Zero Energy Building (NZEB) studies, due to its ability to evaluate the costs indirectly incorporated and invested to generate renewable energies. No limitations are mentioned for this technique.

3.4 Ecosystem Methods

The three ecosystem methods mentioned are Ecosystem *Services Analysis* (ESA), Ecological LCA (Eco-LCA) and Habitat Change Potential for which no details are given on the limitations. However, Izaola and Akizu-Gardoki [12] state that only the inclusion of ecosystem functions or structure is an advantage. Besides being a freely available *online*

tool, Ecological LCA, according to Srinivasan et al. [16], it expands the boundaries of the system and examines the impacts on ecosystem services that are not studied by other tools [13]. On the other hand, the authors state that the Eco-LCA model uses only monetary values as inputs and has similar problems to those inherent in EIO-LCA. Azari [13] states that this method does not allow the comparison of buildings that use products of different origins within a construction sector.

And as far as Ecosystem Services Analysis is concerned, it is the only one that directly relates the impacts of building materials to ecosystem services. However, Zari [19, 20] states in her studies that due to the lack of development and research on the subject, there are no concepts or relationships between the various types of materials and the exact quantitative impact they have on ecosystems. There are no quantifiable ecosystem service metrics for each material, except when calculated for specific projects in specific locations. Applying this method, therefore, requires a complex, multi-scalar and multidisciplinary approach. In addition, the globalisation of production makes it difficult to obtain data on the various processes used in manufacturing.

4 Conclusion

We conclude that numerous methods are currently available, grouped into four classes, which incorporate ecosystem concepts into LCA for the construction sector to varying degrees. This study also highlights the advantages and, in particular, the limitations previously identified in the literature regarding these methods, such as the absence of a common metric for assessing the impacts of construction materials on different ecosystem services, the subjectivity and uncertainties involved, the high data requirements, the inherent complexity of the approaches, the challenges of quantifying non-market aspects, and the difficulties associated with defining and assessing system boundaries and life-cycle stages.

Consequently, the results indicate that ES are still not adequately integrated into LCA for buildings and construction materials, as existing methods face substantial constraints. Based on the findings, "methods" may not be the most effective means through which ecosystem services can be incorporated into LCA, which opens possibilities for future reviews aimed at answering the question: *what types of artefacts or assessment tools are currently being used to integrate ecosystem services into LCA?*

It is also recommended that future reviews draw upon additional databases, as other relevant studies may not have been captured in the present search and could contribute to answering this question. Therefore, there is a clear need to develop a new assessment tool capable of evaluating the impacts of construction materials on ES, overcoming the limitations identified here and supporting built-environment professionals in material selection—potentially functioning as a certification mechanism and contributing to greater circularity in the built environment.

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Energy Impacts of HVAC Systems in Building Life Cycle Assessments: A Case Study Approach

Doris Österreicher[1,2(✉)], Andrea Agner[1], and Hans Werner Roth[3]

[1] Institute for Building Materials, Building Physics, Building Systems and Design, University of Stuttgart, Stuttgart, Germany
doris.oesterreicher@ibbte.uni-stuttgart.de
[2] Treberspurg & Partner Architekten, Vienna, Austria
[3] Tamm, Germany

Abstract. Reducing CO_2 emissions in the built environment requires a comprehensive understanding of impacts across all life-cycle stages of buildings. Current Life Cycle Assessment (LCA) frameworks predominantly focus on operational energy use and, increasingly, on the embodied impacts of construction materials. However, heating, ventilation, and air-conditioning (HVAC) systems - despite their critical influence on both operational performance and embodied emissions - remain largely underrepresented in existing LCA practices. This omission risks overlooking substantial carbon contributions associated with the production, maintenance, replacement, and end-of-life stages of mechanical equipment. This paper addresses this methodological gap by examining how HVAC systems can be systematically integrated into building LCAs, with particular emphasis on highly efficient and renewable energy systems. First, key characteristics of HVAC components and their material compositions are analyzed to identify the inventory data required for embodied carbon calculations. Second, the study proposes an approach for linking equipment lifespans, maintenance cycles, and replacement schedules with the building's operational phase to produce more accurate long-term emission profiles. The interaction between the embodied impacts of energy systems and their operational performance is discussed, highlighting potential trade-offs and synergies when selecting low-carbon technologies. Therefore, the case study highlights that differences in the HVAC system configuration affect the total life-cycle emissions and underlines the need to explicitly integrate HVAC equipment into whole LCAs to avoid substantial underestimation of true building emissions.

Keywords: HVAC systems · Building LCA · Operational energy demand · Embodied Carbon

1 Introduction

The building sector is of critical importance in achieving national and international climate protection goals. In addition to reducing operational greenhouse gas (GHG) emissions, research and regulation are increasingly focusing on the entire life cycle of

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buildings. In Germany, the energy efficiency of buildings is regulated primarily by the Building Energy Act, which aims to minimize the non-renewable primary energy requirement during operation [1]. Alongside this, holistic assessment approaches are gaining importance, incorporating not only the use phase but also the construction, maintenance, replacement, and demolition of buildings. In parallel, holistic assessment approaches are gaining importance, extending the scope to include construction, maintenance, replacement, and demolition [2]. Methodologically, these assessments build on LCA principles according to DIN EN ISO 14040 and DIN EN ISO 14044, which define goal and scope, life cycle inventory, impact assessment, and interpretation [3, 4]. In the building context, DIN EN 15978 specifies the life cycle phases and environmental impact categories to be considered, thereby operationalizing these general principles [2].

Despite the fact that this normative framework calls for the comprehensive coverage of all building-related components and systems, practical applications have often focused on structural elements and the building envelope, and thus increasingly on the embodied carbon of construction materials. Conversely, building services engineering, HVAC systems, are frequently modelled in a simplified or relatively generic manner and are mostly not accounted for in detail in LCA assessments. This is problematic, as HVAC systems significantly affect both operational energy performance and embodied GHG emissions: depending on building type and system configuration, building services equipment can account for approximately 5–20% of the total life cycle GHG potential of residential buildings [5]. For office buildings, contributions between 15% and 36% of total embodied emissions have been reported, while conservative reviews estimate typical shares in the range of 10–12% [6]. HVAC systems therefore cannot be regarded as marginal components; they constitute a substantial source of building-related emissions.

The integration of HVAC systems poses specific challenges due to their comparatively short service lives relative to the building structure. While load-bearing structures are typically designed for reference periods of 50 years or more, many components of technical building equipment exhibit significantly shorter life cycles. In Germany, VDI 2067 is widely used to estimate the economic service life of building services systems; the guideline values provided are often adopted as a basis for replacement assumptions in Module B4 according to DIN EN 15978 [2, 7]. However, these tables were developed primarily for economic evaluations rather than for LCA purposes. Their direct transfer into environmental assessments therefore requires additional assumptions concerning technological development, modernization cycles, actual operating conditions, and the influence of regulatory or innovation-driven replacement decisions, all of which introduce further uncertainty into long-term emission forecasts.

The relevance of technical building equipment is increasingly reflected in the scientific literature. Research on net-zero energy residential buildings shows that the choice of HVAC system has a decisive impact on overall performance, with configuration-dependent trade-offs between operational and embodied emissions. Efficiency gains during the use phase can be accompanied by higher manufacturing impacts, leading to tensions between short-term emission reductions and long-term life cycle optimization [8]. At the same time, methodological uncertainties are highlighted: product-specific environmental declarations are usually only available for a limited set of complex systems, which is why simplified approaches such as material-based estimation methods

or standardized guidelines like CIBSE TM65 are often applied [9]. Comparative studies demonstrate that these methodological choices can result in substantial deviations, particularly for manufacturing impacts and assumptions regarding refrigerant losses during use and at end-of-life.

Systematic reviews further emphasize that building services, despite their material complexity and high replacement frequency, are underrepresented in holistic sustainability and circular economy strategies. A recurring issue is the lack of a consistent linkage between the embodied emissions of building services equipment and their influence on the operational energy performance of the building as a whole. While operational energy use is typically analyzed in detail in Module B6, the underlying technical systems are often represented in an aggregated or simplified manner, which obscures the interactions between efficiency gains and additional material use [10].

In summary, the current state of research shows that the normative framework allows for the comprehensive integration of technical systems, yet practical implementation remains methodologically inconsistent – particularly with regard to data availability, modelling of service lives and replacement cycles, and the coupling of manufacturing and operational phases. Against this background, the present paper aims to address this methodological gap by proposing a structured approach for integrating HVAC systems into building-related LCAs, establishing a robust basis for quantifying both embodied and operational emissions of technical building equipment and thereby enabling more informed decisions on climate-compatible building technologies.

2 Methodology

In order to address the HVAC embodied energy impacts, the LCA is carried out to evaluate the global warming potential (GWP) associated with (1) embodied impacts, (2) maintenance, (3) operation and (4) recycling. The first step is to determine the energy requirements for heating, cooling, and ventilation based on the building's usage requirements and the requirements for thermal comfort and indoor air quality in accordance with DIN EN ISO 7730 and DIN EN 16798-1. The resulting specific energy requirements in kWh/(m^2·a) and the building area form the basis for the selection and dimensioning of the HVAC systems. In this study only the climate impact, expressed as GWP in kg CO_2 equivalents is considered.

Environmental Product Declarations (EPDs) and generic data sets from publicly accessible databases, including ÖKOBAUDAT and EPD International, are used to quantify the embodied emissions of individual components. Since complete product-specific EPDs are not yet available for many components of technical building equipment, embodied emissions are estimated in part using generic material data sets in accordance with the methodology from CIBSE TM65. This is based on a life cycle inventory of the materials used, in which the mass and material composition of the individual products are recorded. The emission factors for the manufacturing phase are taken from modules A1–A3, which cover raw material extraction, material processing, and manufacturing up to the factory gate.

Embodied emissions are initially calculated on the basis of a product's material composition. The emissions from material procurement in module A1 are calculated as

the sum of the products of total product mass, material content, and material-specific emission factor.

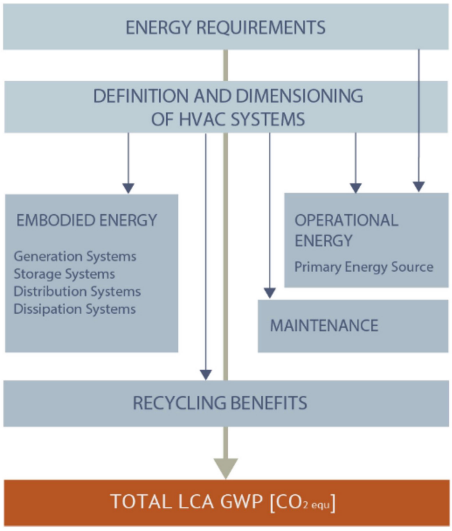


Fig. 1. Aspects of the LCA of a HVAC system.

Further, energy-related emissions from manufacturing are considered. These are allocated to the total quantity produced based on the annual energy consumption of the production facility and assigned proportionally to the product under consideration.

The HVAC systems include all components from energy generation and supply to energy distribution in the building and transfer to room-side components such as air diffusers, panel heating systems, or fan coils. The energy demand at room level determines the dimensioning of the system components and their interactions. For example, heat recovery in ventilation systems reduces ventilation heat losses and thus influences the required output of the heat generators. The efficiency of heat pumps or chillers depends largely on the system temperatures, which is why corresponding flow and return temperatures are considered in the system design. With the increasing share of renewable energies, it is also expected that electrical and thermal storage will be increasingly integrated into building systems.

In addition to embodied emissions, operational emissions during the use phase are also taken into account. See also Fig. 1. These depend largely on the CO_2 intensity of the final energy used. Since both the electricity mix and district heating in Europe will be decarbonized in the long term, it can be assumed that the operational emissions of future building systems will decrease. At the same time, a large proportion of embodied emissions are generated at the beginning of the life cycle during the manufacturing phase. Against this background, the relative share of embodied emissions in the total greenhouse gas emissions of buildings and their technical systems is expected to increase significantly in the future.

3 Case Study: Centralized vs Decentralized Ventilation of a School Room

This study is a scenario-based LCA using representative default parameters due to limited availability of product-specific environmental and service life data for HVAC systems. The results therefore represent comparative system behavior rather than absolute validated emission values. To provide a practical example for the application of the methodology approach, a two-story school with six classrooms is used as a case study. The net floor area of the building is 760 m^2, and a typical classroom has an area of 67 m^2. Two ventilation concepts are compared: (i) a centralized ventilation and air conditioning system (HVAC) with a central ventilation unit in the basement and air-side access to all rooms via a network of air ducts, and (ii) a decentralized solution with one ceiling-mounted ventilation unit per classroom. In both variants, a maximum air volume flow of 1000 m^3/h per classroom is provided in order to limit the CO_2 concentration to around 1000 ppm. In both cases, the air volume flows are regulated as needed via CO_2 sensors. The air is distributed in the room via diffusers and control components integrated into a reversible metal panel ceiling, while the main differences lie in the overall air flow and the arrangement of the system components (centralized vs. decentralized). Furthermore, the two systems differ in their operating hours. By decentralizing the system, the hours can be reduced, resulting in fewer operating hours. The boundary conditions of the study are summarized in Table 1.

For the decentralized variant, the embodied emissions are related to the relevant components of the ventilation system in the classroom. The largest contributions derive from the decentralized ventilation unit itself (ventilation unit AHU: 29 kg CO_2eq; production AHU: 15 kg CO_2eq), as well as the air distribution in the room (diffusers: 28 kg CO_2eq) and the metal panel ceiling (20 kg CO_2eq). Additional emissions are generated by silencers (7 kg CO_2eq), which are required for the maximum permissible sound level of approximately 35 dB(A) in classrooms. In practice, the installation of the units is often supplemented by a ceiling coffering made of metal panels, which serves both design and acoustic functions (Fig. 2a).

In the centralized variant, the highest embodied emissions are attributable to the air distribution network, including outside air intake and exhaust air ducting (centralized air distribution + air intake and exhaust tower: 85 kg CO_2eq). The centralized ventilation unit (33 kg CO_2eq), the metal panel ceiling in the classroom (26 kg CO_2eq), and the room-side diffusers (26 kg CO_2eq) also contribute significantly to the overall balance. The ventilation room itself causes comparatively low emissions (ventilation room: 7 kg CO_2eq). See Fig. 2b. This shows that, in the centralized solution, the overall air ducting and the duct system dominate the embodied carbon balance, while the room-side components are similar in both concepts.

For better comparability, GWPs are based on a single classroom and one year and include embodied carbon (A1–A5), emissions from maintenance (B2–B5), operational emissions (B6), and credits from end-of-life recycling (D). In the decentralized variant, 115 kg CO_2eq/a are attributable to embodied carbon and 26 kg CO_2eq/a to maintenance processes, while the operational emissions of the ventilation system amount to 92 kg CO_2eq/a. In addition, the recycling results in a credit of −20 kg CO_2eq/a.

Table 1. Boundary conditions of the school room used as case study.

School building with two floors, net ground area 2 x 380 m2, 6 class rooms	
Centralized air conditioning system	Decentralized air conditioning system
max.1000 m^3/h/room (1000 ppm CO_2)	
Supply air control bei CO_2-concentration (variable air ventilation)	
Centralized Air-Handling-unit (AHU) in basement	6 decentralized, ceiling based AHU in class rooms
1536 h/a hours of operation per year	1350 h/a hours of operation (natural ventilation)
Centralized preheating at 20 °C (winter)	Decentralized electrical preheating at 17 °C
Supply air cooling optional	
Centralized air distribution in building	Decentralized air distribution in class room
Outdoor air intake-exhaust tower	Facade-integrated weatherproof grille in classroom
Decentralized air distribution, diffusers, controllers installed inside of a reversible suspended metal ceiling	Decentralized AHU, diffusers, installed inside of a reversible suspended metal ceiling

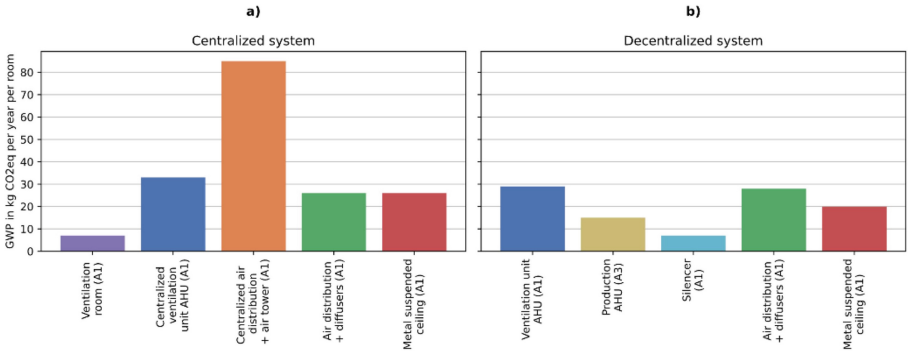


Fig. 2. GWP of the embodied carbon of a) the centralized system and b) the decentralized system.

For the centralized solution, embodied emissions are 181 kg CO_2eq/a, which is significantly higher than the decentralized variant; maintenance causes 32 kg CO_2eq/a. Operational emissions from ventilation amount to 168 kg CO_2eq/a, which is mainly due to higher pressure losses in the central air distribution network. The credit from recycling amounts to −23 kg CO_2eq/a.

Overall, the comparison shown in Figs. 3 and 4 indicates that the decentralized solution results in lower embodied and operational GHG emissions, mainly due to shorter air paths, demand-based control, and reduced fan power.

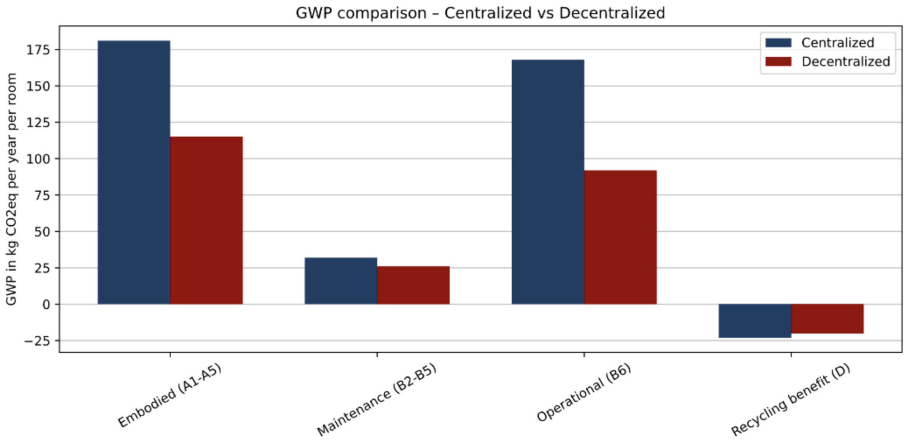


Fig. 3. GWP comparison of centralized and decentralized system in different life cycle stages.

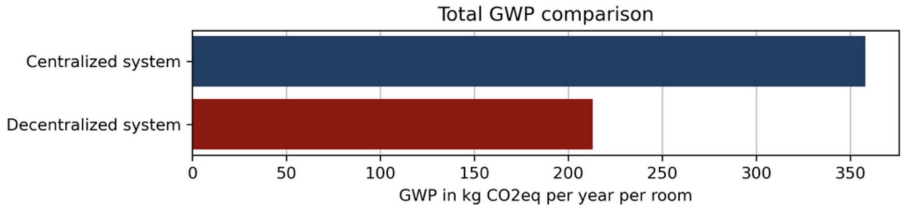


Fig. 4. Total GWP comparison of centralized and decentralized system through the life cycle.

4 Conclusion

In the context of climate protection in the building sector, it will increasingly no longer be sufficient to optimize operational energy efficiency and minimize investment costs for building services engineering alone. The study indicates that HVAC systems can contribute a notable share of total life cycle GHG-emissions, particularly when both embodied impacts and system dependent operational effects are considered. Their relevance is therefore strongly dependent on system design, building type, and boundary conditions, highlighting the importance of their explicit inclusion in building-level LCAs. With the new edition of the Ecodesign Directives (e.g., EU Regulation ESPR 2024/1781 and digital product passport) and the ongoing decarbonization of end-use energy, purely operational metrics are becoming less meaningful, while embodied carbon, material efficiency, and recyclability are gaining in importance.

The proposed approach links material balances, service lives, maintenance cycles, and replacement rates of HVAC components with the operating phase, thus enabling reliable, long-term emission profiles, including possible credits from reuse and recycling. The case study on a school ventilation demonstrates that differences in design and system architecture have a significant impact on both embodied and operational emissions, and that supposedly “efficient” solutions can be relativized ecologically during operation due to high material and replacement costs. For planning, standardization, and

legislation, this highlights the need to explicitly integrate HVAC systems into whole-life-cycle assessments, to focus on renewable and material-efficient concepts at an early stage, and to base system decisions not only on energy performance indicators but also on holistic GWP balances.

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An ESG-Integrated Environmental Impact Assessment Method for Circular Transformation of the Built Environment

Nadezhda Afyan(✉)

Armenian State University of Economics, 128 Nalbandyan, 0025 Yerevan, Armenia
nafyan15@gmail.com

Abstract. This study proposes an ESG-integrated Environmental Impact Assessment (EIA) method for evaluating sustainability and circular economy performance in the built environment. The research extends conventional EIA by incorporating environmental, social, and governance (ESG) dimensions into a unified lifecycle framework that assesses resource circulation, material and energy flow efficiency, social inclusion, and governance transparency. The method is developed through a comparative analysis of key international ESG frameworks, including the GRI Standards and the EU Taxonomy, and environmental management principles reflected in ISO 14001. It is aligned with Armenia's sustainable finance architecture and the ESG Risk Radar logic of the Central Bank of Armenia. The method is pilot-tested on three Armenian built-environment projects from the manufacturing and infrastructure-related sectors using national EIA documentation, production information, and sectoral risk-screening logic. The proposed ESG-EIA method combines risk-based screening, a 15-indicator ESG matrix, sector-sensitive weighting, ecosystem services assessment, material and energy flow modelling, heat-map visualization, and composite ESG performance scoring. Pilot results demonstrate improved early identification of resource inefficiencies, decarbonization gaps, and social and governance risks compared with conventional EIA practice. The findings show that integrating ESG metrics into EIA enhances the robustness of sustainability assessment and supports evidence-based investment, urban planning, and circular transformation decisions in line with national sustainable finance priorities.

Keywords: Environmental Impact Assessment · ESG Integration · Built Environment · Circular Economy · Risk-Based Screening · Cumulative Impacts

1 Introduction

The transition to circular and low-carbon development models in the built environment has become a major priority of sustainability policy, investment governance, and urban transformation. The sector is closely connected with material extraction, energy use, water demand, land transformation, waste generation, and community impacts. Therefore, assessment methods need to capture direct, cumulative, and lifecycle-based risks.

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Environmental Impact Assessment (EIA) remains the main regulatory instrument for identifying and mitigating project-level environmental risks. Yet conventional EIA is not always connected to social accountability, governance transparency, financial risk screening, and circular economy performance. Issues such as material efficiency, decarbonization potential, stakeholder impacts, and monitoring capacity may therefore remain fragmented across separate documents.

Environmental, social, and governance (ESG) frameworks have become central to sustainable finance and investment decisions. The EU Taxonomy supports sustainable investment classification, while the GRI Standards structure impact reporting and ISO 14001 supports environmental management systems [1–3]. For Armenia, this creates an opportunity to connect project-level EIA evidence with finance-oriented ESG risk assessment.

The Armenian context illustrates this need. Circular initiatives in the Pambak and Spitak communities, including greenhouse production, stone veneer manufacturing, dairy production, cold-storage services, and slaughterhouse operations, show both environmental pressures and circular opportunities. Large enterprises more often operate under formal EIA, ESG disclosure, and management systems, while SMEs usually have weaker reporting capacity but greater flexibility in resource reuse and process adjustment.

Building on these observations, this study proposes an ESG-integrated EIA method for evaluating sustainability and circular economy performance in the built environment. The method is designed for both large enterprises and SMEs and assesses resource circulation, material and energy efficiency, social inclusion, governance transparency, and sustainable finance relevance.

2 Literature Review

The literature emphasizes the increasing role of ESG criteria in infrastructure planning, corporate governance, and investment decision-making. ESG can complement EIA by translating environmental evidence into indicators understandable for regulators, investors, and enterprise managers [5–8].

International frameworks provide the basis for this integration. The EU Taxonomy links sustainable activities to climate, circular economy, pollution, water, and biodiversity objectives [1]. The GRI Standards structure sustainability impact reporting [2], while ISO 14001 emphasizes planning, monitoring, corrective action, and continual improvement [3].

SMEs represent the majority of enterprises [9], but ESG reporting and certified environmental management systems remain concentrated mainly among larger companies. SMEs represent the majority of enterprises, but ESG reporting and certified environmental management systems remain concentrated mainly among larger companies. This creates a governance gap: SMEs may have significant cumulative material, energy, water, and waste impacts, yet limited administrative capacity for complex reporting.

For Armenia and similar transition economies, sustainable finance initiatives increase the need for comparable ESG information. The Central Bank of Armenia's sustainable finance work and ESG Risk Radar logic emphasize sectoral exposure to climate-related, environmental, social, and governance risks [4].

Overall, the literature reveals a methodological gap in the systematic integration of ESG indicators and circular value-chain logic into EIA. This study addresses that gap by proposing a 15-indicator ESG-EIA framework for cumulative impact assessment, lifecycle interpretation, and finance-oriented decision-making.

Environmental assessment effectiveness depends on its influence on decisions and implementation [10]. However, ESG indicators and circular value-chain logic remain insufficiently integrated into EIA. This study addresses that gap by proposing a 15-indicator ESG-EIA framework for cumulative impact assessment, lifecycle interpretation, and finance-oriented decision-making.

3 Methodology

3.1 Research Design and Conceptual Framework

The research applies a conceptual and pilot-testing design. International ESG and environmental management frameworks were compared to identify indicators relevant to circular transformation. These indicators were then translated into an ESG-integrated EIA matrix and tested on three Armenian pilot cases: "Qaradzor Agro", "Hope Labe", and "Makur Bnutyun". The assessment used EIA documentation, project descriptions, available production and resource-use information, and sectoral risk-screening logic aligned with Armenia's ESG Risk Radar approach [4].

The framework covers five lifecycle stages: input, production, distribution/use, end-of-life, and reintegration. This structure moves the analysis beyond isolated project impacts and shows how environmental, social, and governance risks accumulate across the value chain. The reintegration stage is essential for circular economy assessment because it captures reuse, secondary materials, and waste-to-resource feedback loops (Fig. 1).

3.2 ESG Indicator Matrix and Parameters

To improve transparency and reproducibility, the framework uses 15 indicators grouped into environmental, social, and governance sub-indices. The indicators were selected according to relevance to circular transformation, measurability through EIA or enterprise-level information, and applicability to both large organizations and SMEs. Table 1 operationalizes each indicator.

Table 1. ESG-EIA indicator matrix and operational parameters (Source: author's own elaboration)

Sub-index	No.	Indicator	Specific parameter	Measurement	Main source
E	E1	Material intensity	Quantity of primary or secondary material per unit of output	kg or t/unit	EIA, production records

(*continued*)

Table 1. (*continued*)

Sub-index	No.	Indicator	Specific parameter	Measurement	Main source
E	E2	Energy intensity	Energy consumed per unit of output or service	kWh or MJ/unit	Energy records, technical data
E	E3	Water intensity	Water consumed per unit of output, area, or service	m3/unit	EIA, permits, enterprise records
E	E4	Emissions intensity	Direct and indirect emissions related to production or operation	tCO2e/unit	EIA, fuel and energy data
E	E5	Waste and recycling rate	Share of waste reused, recycled, or diverted from disposal	%	Waste management plan
S	S1	Occupational safety	Accident exposure, safety measures, and worker risk controls	score 0–1	EIA, enterprise data
S	S2	Local employment	Share of jobs or contracts involving local communities	%	Project records
S	S3	Community impact	Noise, traffic, odour, land-use conflict, and nuisance exposure	score 0–1	EIA, public consultations
S	S4	Inclusion and access	Participation of vulnerable groups and access to benefits	score 0–1	Project documentation
S	S5	Health and sanitation risk	Potential sanitary, hygiene, and public health risks	score 0–1	EIA, sanitary assessment
G	G1	Compliance status	Permits, EIA decision, legal conformity, and reporting duties	score 0–1	Regulatory documents
G	G2	Risk management system	Presence of procedures for identifying and managing ESG risks	score 0–1	Management documents

(*continued*)

Table 1. (*continued*)

Sub-index	No.	Indicator	Specific parameter	Measurement	Main source
G	G3	Monitoring and responsibility	Existence of monitoring plan, indicators, and responsible persons	score 0–1	EMP, EIA report
G	G4	Transparency and disclosure	Availability of public information, reporting, and stakeholder feedback	score 0–1	Reports, website, hearings
G	G5	Financial and ESG alignment	Compatibility with banking ESG risk screening and sustainable finance criteria	score 0–1	Loan documents, ESG radar logic

3.3 Normalization, Weighting, and Sector-Sensitive Interpretation

Each indicator is normalized on a 0–1 scale, where 0 reflects weak performance or high unmanaged risk and 1 reflects stronger performance or lower managed risk. Quantitative indicators are normalized using benchmark or relative values, while qualitative indicators are scored through documentary evidence, expert judgment, and the presence of formal procedures. Sub-indices and the composite ESG-EIA score are calculated as weighted averages.

The weighting system was designed as a baseline framework applicable across the pilot cases. However, sector-specific sensitivity was considered during interpretation because ESG risks differ by project type. For example, sanitary and community risk indicators receive greater analytical attention in slaughterhouse-related activities; resource efficiency, process waste, and material circularity are more significant in stone manufacturing; while greenhouse production requires closer attention to water and energy intensity. Therefore, the proposed weighting approach combines a common ESG structure with sector-sensitive interpretation rather than applying a mechanically uniform assessment logic across all sectors.

The assessment process includes five steps: risk-based screening, ecosystem services assessment, material and energy flow modelling, heat-map visualization, and composite ESG scoring. This sequence identifies high-risk lifecycle stages, evaluates land, water, and biodiversity impacts, estimates circularity opportunities, and summarizes ESG performance for decision-making.

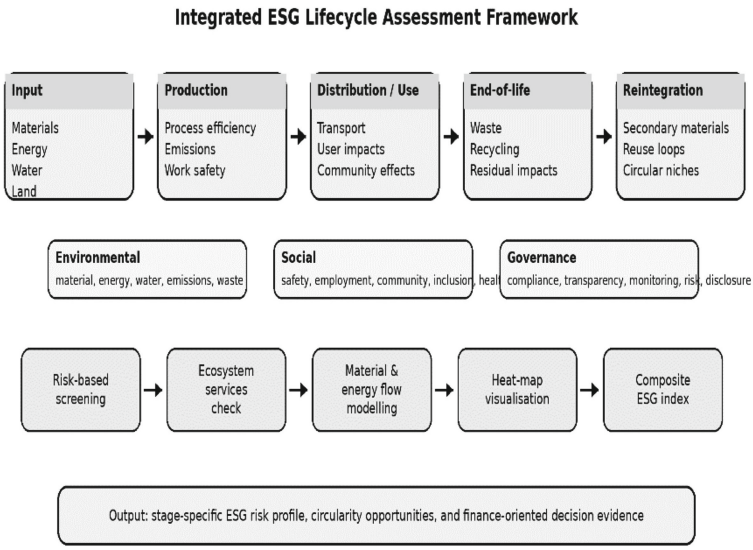


Fig. 1. Integrated ESG lifecycle assessment framework (Source: author's own elaboration)

4 Results and Discussion

4.1 Pilot Results

The pilot application shows that ESG-integrated EIA enables earlier identification of resource inefficiencies, decarbonization gaps, and social and governance risks. Compared with conventional EIA, it better captures how environmental impacts interact with social vulnerability, monitoring capacity, and finance-oriented ESG risk signals.

In "Qaradzor Agro", the input and production stages revealed potential water savings of approximately 14% and energy savings of about 9%, mainly linked to irrigation and greenhouse energy management. In "Hope Labe", the production stage showed approximately 15% potential for material flow optimization through process waste reduction and partial use of secondary materials. In "Makur Bnutyun", production and distribution stages showed higher emissions, water, sanitation, and community-impact risks, indicating that conventional EIA alone may not fully capture the combined ESG profile (Table 2).

Table 2. Comparative pilot results of the ESG-integrated EIA method (Source: author's compilation based on the pilot assessments)

Case	Dominant lifecycle risk	Key ESG issue	Circular opportunity	Assessment implication
Qaradzor Agro	Input and production	Water and energy intensity	Irrigation optimization and energy saving	Environmental indicators dominate, but monitoring capacity determines bankability
Hope Labe	Production and reintegration	Material intensity and process waste	Secondary material use and waste reduction	SME flexibility supports circular niche development
Makur Bnutyun	Production and distribution	Water, emissions, sanitation, and community impact	Wastewater control and logistics improvement	Social and governance safeguards require stronger weighting

4.2 Reintegration and the Role of SMEs

The results also clarify the role of SMEs during the reintegration stage. Although SMEs often perform weakly in formal governance and accountability indicators, they may have advantages in circular experimentation because they usually have shorter decision-making chains, flexible production routines, and closer control over material flows.

For example, stone veneer manufacturing may reintegrate secondary material streams, greenhouse production may introduce water- and energy-saving practices quickly, and food-processing activities may improve waste separation and by-product handling when technical support is available. SMEs should therefore be viewed not only as compliance-limited actors, but also as potential niche innovators in circular economy implementation.

This finding is important for sustainable finance because ESG-EIA results can help banks distinguish between weak documentation and genuine circular improvement potential. This supports targeted lending, technical assistance, and staged compliance pathways for SMEs.

4.3 Contribution to EIA Practice and Sustainable Finance

The framework contributes to EIA practice by linking project-level evidence with ESG indicators, expanding assessment to lifecycle stages, and enabling comparison across activities through a common matrix with sector-sensitive interpretation.

The method supports Armenia's sustainable finance priorities by improving the traceability of environmental and social information. EIA documents often contain data on resources, emissions, waste, land use, and mitigation measures, but these data are not always organized for ESG risk assessment. The proposed method reorganizes this information without replacing the legal EIA procedure.

At the policy level, ESG-integrated EIA can strengthen circular economy governance in the built environment, support differentiated requirements for large enterprises and SMEs, and improve information quality for sustainable investment decisions. Its accuracy depends on EIA data quality, enterprise-level resource records, and consistent expert scoring.

5 Conclusion

This study developed and pilot-tested an ESG-integrated Environmental Impact Assessment method for circular transformation of the built environment. The method extends conventional EIA through a lifecycle-based 15-indicator ESG matrix, sector-sensitive weighting, risk-based screening, ecosystem services assessment, material and energy flow modelling, heat-map visualization, and composite ESG scoring.

The pilot cases show improved early identification of resource inefficiencies, decarbonization gaps, and social and governance risks. "Qaradzor Agro", "Hope Labe", and "Makur Bnutyun" demonstrate that environmental risks concentrate mainly in input and production stages, while cumulative and indirect effects become more visible during distribution, end-of-life, and reintegration. SMEs may be weaker in formal governance, but stronger in flexible circular experimentation.

The main contribution of the study is the methodological bridge between EIA, ESG assessment, circular economy logic, and sustainable finance. The framework can help regulators improve sustainability assessment, banks evaluate ESG-related project risks, and enterprises identify practical circular transformation opportunities.

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The Relevance of the End-of-Life for Earth Blocks to Evaluate Their Circularity Potential and Environmental Impact

Laura Claes(✉), Griet Verbeeck, and Elke Knapen

Faculty of Architecture and Arts, Hasselt University, Diepenbeek, Belgium
laura.claes@uhasselt.be

Abstract. In the shift toward the use of low-impact and more circular materials, there has been an increase in life cycle assessments (LCAs) of earth-based constructions to quantify their environmental impact. In these evaluations, the end-of-life (EOL) plays a crucial role, as it can significantly enhance their circularity potential and, therefore, reduce their environmental impact. However, benefits and loads related to the EOL are often overlooked in current LCAs. Hence, this study aims to contribute to the ongoing debate on EOL evaluation for circular earth products, specifically earth blocks, through a targeted literature review and an LCA to assess the environmental impact of earth block applications. Given the relatively recent reintroduction of earth blocks in contemporary construction, their EOL processing has yet to be established. Therefore, specific attention is given to current key factors concerning present and possible future EOL scenarios for earth blocks. In addition, qualitative indicators that are currently not included in the LCA methodology, such as longevity, regenerative potential, and renewability (multiple life cycles), relevant for the circularity potential and environmental impact, are investigated. The study revealed that EOL scenarios for earth blocks are underdeveloped, leading to neglect of the aforementioned indicators in the current LCA methodology. Together with its quantitative nature, LCA is only partially suited for EOL evaluation of circular earth products, failing to capture their environmental and circular potential. A better understanding of the importance of the EOL and its associated impact will facilitate the further development of possible EOL scenarios for earth block applications.

Keywords: Life Cycle Assessment · Earth blocks · End-of-life · Circularity · Environmental Impact

1 Introduction

Over the past decades, the growing awareness of the high embodied energy of conventional construction materials and the ongoing depletion of natural resources [1] has led to renewed interest in low-impact and more circular materials. As a result, the use of earth-based building materials, such as earth blocks, is becoming more prevalent in real-life applications, as their possible environmental benefits are increasingly recognised

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[2]. To quantify their environmental impact and facilitate comparison with conventional building materials [3], in the last few years, a growing number of life cycle assessments (LCAs) of earth-based building materials have been conducted [4]. In these environmental evaluations, the end-of-life (EOL) is essential. Any associated impacts, both positive and negative, must be considered, especially for building materials that can be reused or recycled, such as earth blocks [5]. For this reason, how earth products are treated at the EOL can enhance their circularity potential and thereby reduce environmental impact. However, the EOL is often not included in current LCAs and, if it is, landfill is the only possible EOL scenario considered, as the chosen system boundary for the majority of the LCAs is cradle-to-gate [2, 4]. This exclusion of the EOL results in a limited understanding of its potential benefits and loads, and, moreover, the relationships between EOL scenarios, environmental impact and circularity. Hence, to address this knowledge gap, the main objective of this study is to add to the ongoing discussion on EOL evaluation of circular earth products, with a specific focus on earth blocks. Provided that possible EOL scenarios are not yet established due to the recent adoption of earth blocks in contemporary construction, current key factors concerning present and potential future EOL scenarios are examined through a targeted literature review. In addition, the study explores qualitative indicators that are currently overlooked in LCAs and can contribute to the environmental and circular potential of earth blocks. The limitations of EOL evaluation in LCA methodology are investigated, building on the authors' ongoing research, namely an LCA study of non-load-bearing, earth-block-based partition walls, with the aim of providing a more complete perspective on the potential of earth blocks.

2 Methods

The methodology follows a two-step approach to identify qualitative indicators that are frequently omitted from current LCAs. Initially, key factors related to present and possible future EOL scenarios were determined through a targeted literature review. This phase focused on synthesising common hurdles in today's industry related to the EOL of earth blocks, highlighting recurring gaps in EOL treatment. Subsequently, building on this review of existing literature and the authors' ongoing LCA study of non-load-bearing, earth-block-based partition walls, a set of overlooked qualitative indicators was developed. By conducting the LCA study and, therefore, experiencing its boundaries, specific, often underrepresented indicators critical to evaluating the EOL of earth blocks were derived. Modelling the different LCA stages, particularly the EOL, revealed qualitative variables that the current LCA methodology does not capture. While the LCA study provides empirical grounding for identifying these indicators, the quantitative results of this LCA are outside the scope of this paper. It focuses strictly on the indicator framework itself.

3 Results

3.1 Key Factors Concerning Present and Possible Future End-of-Life Scenarios

As earth blocks are non-standardised products and their application in mainstream construction remains relatively novel, there is a limited understanding of their EOL handling. While their manufacturing and construction techniques have been studied, EOL

constraints and drivers have received less attention [6]. Nonetheless, the EOL is crucial since the use phase of earth blocks will eventually end [7]. Hence, key factors related to EOL scenarios, focusing on the incorporation of recycled materials, stabilisation and waste treatment strategies, are investigated.

Incorporation of Recycled Materials and Stabilisation. Over the years, in the production of earth blocks, efforts have focused on integrating reclaimed excavated material and construction and demolition waste (CDW) to enhance their environmental performance. Excavated material can be recovered from construction sites, offering environmental benefits over disposal [8]. Additionally, the use of CDW (e.g. crushed concrete or brick rubble) has been explored [9]. Nevertheless, although secondary raw materials are used for production, the recycling of earth blocks remains unestablished in practice, despite promising mechanical performance results [10].

Furthermore, unstabilised earth blocks have limited water resistance [11] and lower strength [12] than conventional materials. To improve these properties, additives such as lime or cement are sometimes added as stabilisers. However, this increases the environmental impact during production [13] and affects EOL processing, compromising recyclability [10]. Hence, the recyclability potential of earth-based materials and the effects of stabilisation should be investigated.

Waste Treatment Strategies. At the EOL, earth-based building materials can be reused, recycled, or disposed of, with reuse preferred. However, reuse may not always lead to lower environmental impact due to transportation impacts and disassembly processes [14]. Recycling is complicated by the mixing of earth block waste with conventional materials [7], hindering its effectiveness. Concerning disposal, unstabilised earth products can return to nature because they are chemically unaltered [15], but challenges remain, including legal restrictions on environmental disposal and changes in soil composition from mixing different earth sources and using CDW. For stabilised products, this is even more challenging, as chemical transformations occur.

Therefore, a thorough evaluation of these EOL scenarios and their effect on the environmental impact is required. Fig. 1 shows the current situation for unstabilised and stabilised earth blocks, along with future scenarios. Currently, these materials are treated like conventional building materials, with a small percentage being landfilled and most repurposed as gravel. Some Environmental Product Declarations [16, 17] explore reuse and recycling for new earth blocks, through take-back programs. A more differentiated approach in the future could enhance EOL management, promoting recycling and reuse and encouraging a return to nature rather than landfill.

3.2 Overlooked Qualitative Indicators in LCA Methodology

Current research employs LCA to quantify the environmental impact of building materials. This method allows for the assessment of the EOL, which involves both waste treatment and benefits and loads beyond the system boundary. However, as a quantitative tool, it has its limitations. It often omits qualitative indicators essential to EOL evaluation, thereby obscuring the circular and environmental potential of earth blocks. Therefore, this section discusses three valuable, though underrepresented, qualitative indicators: the material's longevity, regenerative potential, and renewability.

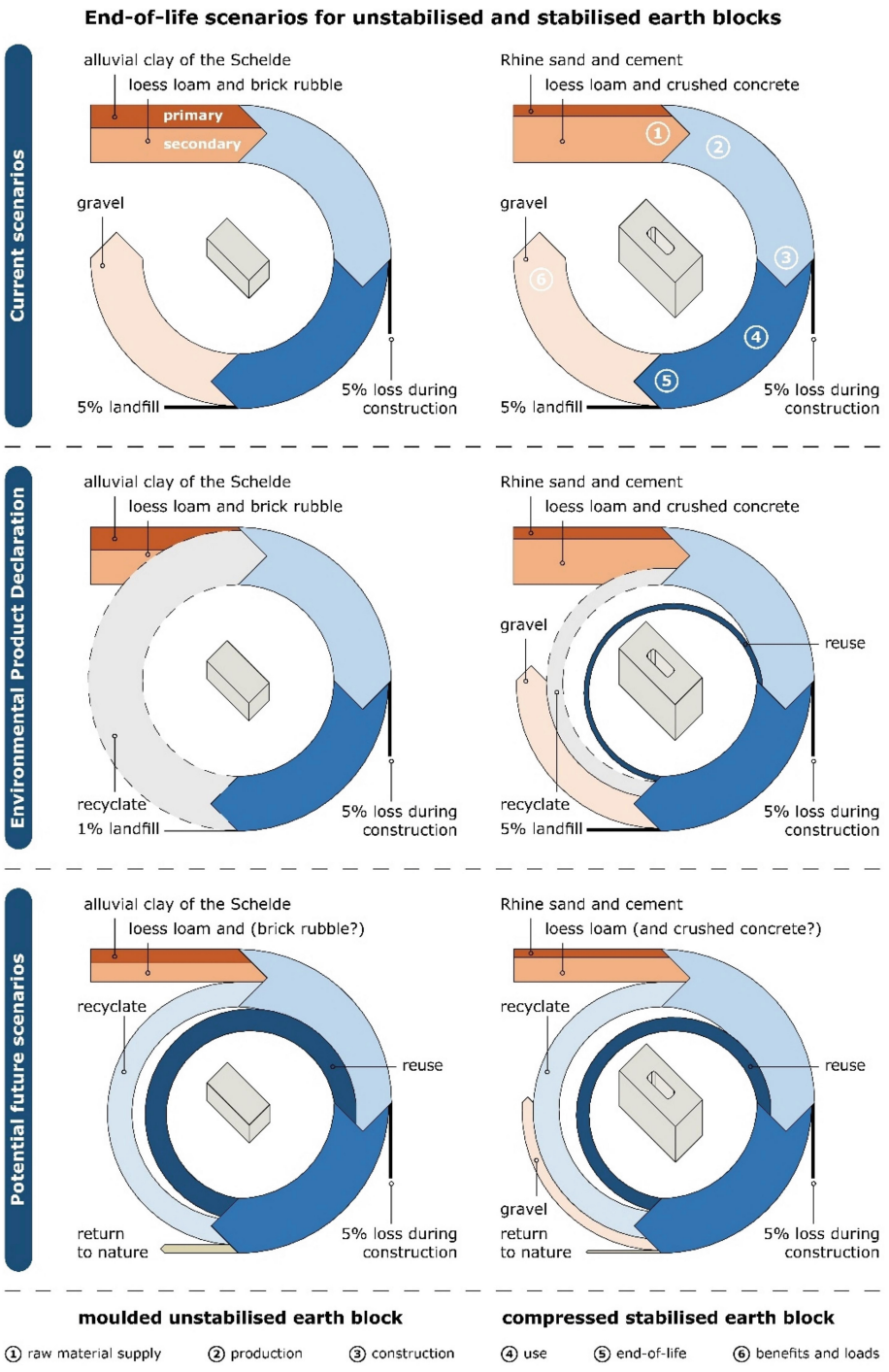


Fig. 1. Present and possible future EOL scenarios for unstabilised and stabilised earth blocks

Longevity. While the EOL of building materials can provide benefits, extending their lifespan should be prioritised. Preventing replacement reduces environmental impacts associated with waste and production. Therefore, longevity is critical, and its inclusion has been recommended for LCAs [18]. However, maintenance and repairs are often not accounted for, or lack transparency in LCAs, and replacement is assumed instead [2]. Furthermore, in Europe, the lifespan is estimated at 50 to 60 years, though the benefits of repair may only be evident over longer periods. A longer reference service life would encourage the use of repairable materials, but it would shift the focus away from the initial environmental impacts [19].

For earth-based materials, repairability is crucial. Unstabilised earth blocks can be repaired with leftover soil, enhancing their lifespan, whereas stabilised earth blocks pose greater challenges due to chemical changes induced by the stabilisation process.

Regenerative Potential. To transition to a circular economy (CE), it is integral to adopt a model that promotes regenerative materials. One aspect of regenerative architecture focuses, namely, on long-term resource availability and maximising the material's value [20]. Nevertheless, the regenerative potential of earth-based materials, such as earth blocks, is undervalued in current LCA methodology. Although these materials are geo-based and non-replenishable, two key attributes of regenerative building are often disregarded: their local resource availability and reversibility.

Local Resource Availability. Using recuperated earth from excavation activities for earth block production is well established. In LCA studies, these benefits are accounted for by attributing the environmental impact of soil extraction to the original excavation activity [2]. Despite allocation concerns, this reduces the impact of earth block production, as shown in Fig. 1, where primary and secondary resources are distinguished. Additionally, local sourcing, which is possible due to soil's wide availability, minimises transportation impacts, a significant factor in the overall environmental performance of earth-based materials [2]. However, LCA methodology does not recognise all advantages of local earth availability, overlooking, for example, its contribution to local economic development, including supply chain resilience.

Reversibility. One possible future EOL scenario for the material is a return to nature, as shown in Fig. 1 for both stabilised and unstabilised earth blocks. The benefit of this scenario is that no waste is left behind, as the material integrates into the ecosystem. Yet, regulatory frameworks remain inadequate, and an LCA does not indicate reduced environmental impact for this scenario. The avoided-burden approach, used to calculate benefits and loads per the EN15804 standard, considers reuse, recycling, and incineration, but does not account for a return to nature. Consequently, by only recognising these scenarios as beneficial EOL options, the continued production of building materials may inadvertently be encouraged.

Renewability.
Traditional LCA studies often focus on a single life cycle. However, the advantages of circular EOL scenarios only become evident when evaluating multiple life cycles [21]. For earth blocks, this multi-cycle perspective is crucial, as they could have closed-loop

material flows [22]. Therefore, their renewability through reuse and recycling, along with the associated benefits and loads, should be assessed.

Reuse. Reusing building materials can significantly reduce environmental impacts by decreasing resource extraction, lowering the risk of depletion, and minimising waste [23], as demonstrated in Fig. 1. While some studies have shown that reusing earth-based materials is feasible, standards for this EOL scenario are lacking [22]. Nevertheless, current LCAs use multiple allocation approaches for EOL impacts, leading to different distributions of benefits and loads among subsequent life cycles [21]. This lack of consensus on assigning environmental impacts associated with the EOL [4] limits the recognition of reuse's advantages.

Recycling. Recycling can reduce environmental impacts by processing waste into new building materials [23], which affects primary resource demands, as shown in Fig. 1. Unstabilised earth blocks can be crushed and sieved to restore their original components [15], while stabilised blocks can be crushed and used to replace coarse granulates. As a result, this recycling process minimises the impacts of excavation, transportation and mixing, and reduces raw material requirements [22]. However, in a classic LCA, recycling yields only limited additional benefits in the next life cycle since the use of secondary raw materials is already integrated into earth block production. This complicates its quantification, making the expression of its benefits unclear.

4 Discussion and Conclusion

While the EOL is crucial for enhancing the circularity and environmental performance of earth-based applications, it is often excluded from LCAs. This omission hinders the understanding of EOL benefits and loads. To fill this gap, this research aims to contribute to the ongoing discussion on EOL assessment of earth products, particularly earth blocks. Key factors regarding their EOL scenarios, along with overlooked qualitative indicators in LCA methodology, were examined.

The study highlighted that, while earth blocks can be reused, recycled, or disposed of, their EOL scenarios are underdeveloped and similar to those of conventional materials. This affects EOL evaluation in LCA methodology, as qualitative indicators are often overlooked. Longevity is frequently neglected, with the reference service life in a classic LCA being too short, and repairing earth blocks is rarely considered. Regarding regenerative potential, local material sourcing and recovery yield benefits, though these benefits primarily stem from reduced transportation and excavation impacts. A return to nature at the EOL does not reduce impact, since it does not prevent manufacturing or energy impacts. Concerning renewability, reuse avoids production processes, yet its benefits are unevenly distributed across life cycles due to multiple allocation methods. Recycling has limited advantages, as the use of secondary resources is already embedded in earth block production, resulting in a lower initial impact.

The findings suggest that, while established, the LCA method needs improvement in its EOL evaluation. Its quantitative nature excludes factors such as longevity, regenerativity and renewability, limiting the tool's suitability for circular earth products. Future research should analyse current and future EOL scenarios for earth blocks and similar

materials to enhance understanding of waste management and the role of stabilisation. Additionally, examining EOL evaluations for circular products will help model EOL pathways and consider multiple life cycles. Overall, this study underscores the importance of the EOL and its assessment for developing earth products.

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Exploring Timber–Mycelium Hybrid Components for Circular Building Construction

Giorgio Castellano(✉), Federica Pradella, Pietro Augusto Falcinelli, and Ingrid Maria Paoletti

Politecnico di Milano, Piazza Leonardo da Vinci 32, Milan 20133, Italy
giorgio.castellano@polimi.it

Abstract. European policy agendas increasingly position the built environment as a priority field for deep decarbonization and resource efficiency. This paper investigates how bio-based and regenerative materials can support circular construction through the development and preliminary assessment of a timber-mycelium hybrid box-based infill unit for prefabricated timber building systems. The methodology combines targeted literature review, material exploration and iterative prototyping within a material-driven, bottom-up framework. The unit reinterprets sheet-based CNC plywood panel logics as an assembly scaffold and integrated permanent formwork for mycelium-based composite growth, enabling dry assembly and potential selective replacement within timber structural frames (e.g., CLT). Prototyping confirms the feasibility of a compartmentalized plywood frame that supports more uniform colonization and repeatable fabrication. A comparative screening LCA benchmarks the hybrid unit against a conventional insulation proxy, indicating lower embodied impacts under the tested baseline assumptions and highlighting key sensitivities, particularly drying/deactivation electricity. Overall, the study provides proof of concept for circular envelope components and a transparent decision-support workflow for early-stage design iteration.

Keywords: Bio-based Materials · Mycelium · Circular Building Construction · Digital Fabrication · Design for Manufacturing and Assembly · Screening LCA

1 Introduction

Embodied impacts are increasingly recognized as a decisive lever for building decarbonization, especially as operational energy decreases in high-performance envelopes and retrofits [1]. Circular construction frameworks therefore emphasize material efficiency, modularity, and end-of-life strategies that preserve value through reuse, repair, and high-quality recycling rather than downcycling or disposal [2–4]. Disassembly-oriented approaches support maintenance, selective replacement, and higher-value recovery pathways, although environmental outcomes remain scenario-dependent and require consistent life-cycle evaluation [3, 4].

Digital design and fabrication enable these strategies by supporting off-site manufacturing, repeatable part families, dry assembly, and controlled tolerances that facilitate dismantling and component replacement [5]. Prefabricated façade systems and

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timber-based modular envelopes for retrofit and new construction highlight the role of standardized modules and interface logic in feasibility and scalability [6–8]. In this context, Computer Numerical Control (CNC) based sheet timber systems provide an established "grammar" of interlocking joints and connector keys that reduces assembly complexity and part variability while remaining compatible with industrial workflows [9]. Mycelium-based lignocellulosic composites are attracting growing attention as low-density insulation and infill materials, with properties dependent on fungal species, substrate, growth conditions, and post-processing [10, 11]. While experimental studies report promising insulation performance, moisture sensitivity and process control remain key barriers to wider adoption [12]. Recent Life Cycle Assessments (LCAs) indicate potential advantages compared to conventional options but consistently identify manufacturing energy (especially drying/deactivation) and yield as dominant sensitivities that can overturn benefits if not managed [14–16]. More broadly, early-stage LCA integration in bio-based panel development is valuable for hotspot identification and design iteration without over-claiming precision under prototype conditions [13]. Against this background, this study develops a timber–mycelium hybrid infill concept that reinterprets CNC-cut plywood "box" logics as an assembly scaffold and integrated permanent formwork for mycelium growth, enabling dry assembly and selective replacement within timber structural frames (e.g., Cross-Laminated Timber CLT). A screening comparative LCA is used as a decision-support tool and is reported consistently with modular construction LCA logic (A1–A3 as core model) [17].

2 Methodology

The research approach combines (i) targeted literature review, (ii) material exploration and bio-fabrication trials, (iii) iterative prototyping supported by CNC fabrication, and (iv) a preliminary evaluation framed by circularity principles and screening LCA. The workflow (Fig. 1) is informed by circular construction frameworks and disassembly-oriented design lenses, where end-of-life considerations and process constraints guide geometry and system decisions [2–4]. In parallel, a Design for Manufacturing and Assembly (DfMA) oriented perspective supports repeatable part families, simplified fabrication and dry installation workflows enabled by digital fabrication [5, 9].

Bio-fabrication and prototyping steps and parameters are summarized in Table 1.

A comparative screening LCA was structured to support early-stage decision making and hotspot identification rather than definitive quantification. The core model is reported as cradle-to-gate (A1–A3) consistently with modular construction LCA logic [17] and following ISO 14040/44 principles [20, 21]. Background processes were modelled in SimaPro using Ecoinvent v3 (allocation, cut-off) system model datasets [18]. Manufacturing electricity (CNC cutting and drying/deactivation) is treated as a sensitivity parameter, consistent with recent mycelium-composite LCAs that highlight energy demand and yield as dominant drivers [14–16]. The impact indicator used for reporting is GWP100 (IPCC 2021) [19].

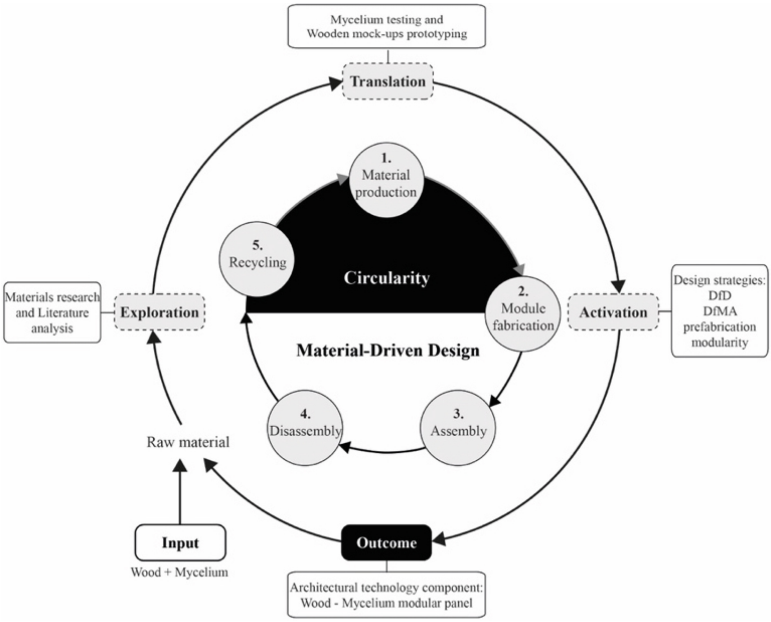


Fig. 1. Diagram of the adopted methodology, integrating material exploration, prototyping and screening LCA within a circular design framework.

Table 1. Bio-fabrication and prototyping steps and parameters

Stage	Key parameters / inputs	Conditions / notes
Recipe (batch)	100 g fibers (substrate) + 25 g flour (nutrient) + 153 g distilled water + 42 g mycelium spawn	Laboratory batch used for prototype trials
Sterilization + Inoculation	Substrate sterilized; inoculated with *Pleurotus ostreatus*	Hygienic protocol to minimize contamination
Incubation	–	7 days at 25–30 °C
Scale test	Colonized substrate transferred to 1:2 mock-up	Behavior within mould geometry; validation of open-box formwork
Pilot unit assembly	CNC-cut plywood open-box disinfected and filled	Internal ribs define cavities; dry assembly
Closed colonization	Unit closed with final back element	~10 days colonization; mould thickness ≈ 7 cm
Deactivation	–	Drying at 70 °C to deactivate metabolism and stabilize [10, 11].

3 Timber–Mycelium Hybrid Component Development

The timber–mycelium element is presented as a prefabricated box-based infill unit assembled from CNC-cut plywood parts. The unit integrates a bio-based core within a dry-assembled frame and compartmentalized cavities, enabling selective replacement and potential recovery within a modular timber envelope. At building scale (Fig. 2) it acts as a non-structural enclosure layer hosted by a load-bearing timber structure (e.g., CLT grids). Interface flexibility is restricted to the unit-to-frame connector set; alternative interfaces (e.g., metallic brackets) are treated as project-specific adaptations that may affect disassembly potential and circularity scenarios [2–4].

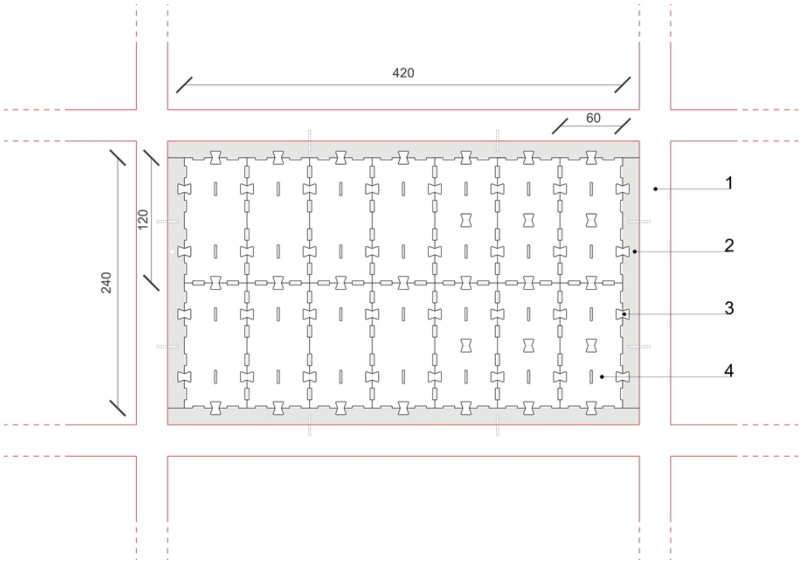


Fig. 2. Façade-scale modular layout of the box-based infill system within a timber structural grid (e.g., CLT). Infill units are tessellated to form the non-structural enclosure layer and connected through dry reversible keys. (1) host structural frame; (2) unit-to-frame connector set; (3) unit-to-unit connector key; (4) box-based infill unit. Credit: by Authors

The unit is engineered as an integrated permanent formwork for a mycelium-based composite core. Sheet-based interlocking logics typical of CNC timber systems (tab/slot assembly and connector keys) are adapted to a hybrid bio-based infill while keeping fabrication compatible with standard CNC routers and dry assembly [9]. This approach is consistent with open-source, CNC-cut timber systems such as WikiHouse, where tab/slot assembly and connector keys enable rapid dry assembly from sheet materials [9]. The core is treated as a non- or semi-structural insulation/infill material whose properties can be tuned through fungal species, substrate selection and process variables [10, 11]. A pilot unit (Fig. 3) was developed to validate joinery, compartmentalization and bio-fabrication workflow and to define the functional unit for the screening LCA (Sect. 4); the pilot geometry should not be interpreted as a prescribed façade module size.

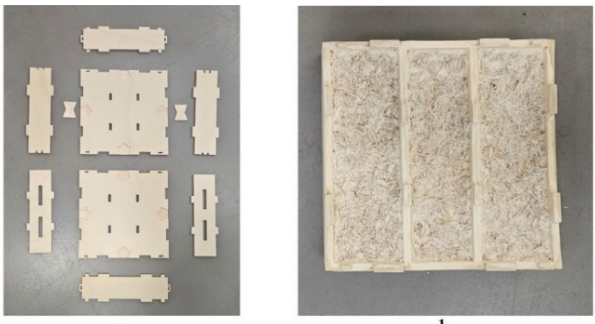


Fig. 3. Prototype development of the timber–mycelium box-based infill unit: (a) CNC-cut plywood parts prior to assembly; (b) assembled open-box frame with internal ribs, filled with inoculated lignocellulosic substrate for colonization. Credit: based on C. Assirelli & A. Crocicchia (MSc Thesis, Politecnico di Milano, 2024). Pictures: G. Castellano.

The manufacturing workflow integrates bio-fabrication within CNC-based timber fabrication through a repeatable sequence (Fig. 3): (i) CNC cutting of plywood parts; (ii) dry assembly of an open-box frame with internal ribs; (iii) filling with inoculated lignocellulosic substrate and incubation to complete colonization; (iv) closure to stabilize confinement; and (v) drying/deactivation to stabilize the composite core and bonding to internal surfaces. This sequence minimizes auxiliary formwork materials and translates mycelium growth into a reproducible workflow suitable for iterative prototyping and scale-up.

4 Screening Comparative LCA

A comparative screening LCA was conducted to provide early-stage feedback on the embodied climate impacts of the timber–mycelium box-based infill unit. The assessment follows ISO 14040/44 principles and is reported as cradle-to-gate (A1–A3) in line with EN 15804 modular terminology; modules beyond A1–A3 are treated as optional scenarios and are not included in baseline claims [17, 20, 21]. The impact indicator is GWP100 (IPCC 2021) [19]. Functional unit (FU): one pilot infill unit (600 × 600 × 180 mm), including the plywood frame and full core volume. A performance-based FU (e.g., per m^2·K/W) is not adopted because prototype thermal performance is not yet validated. Foreground quantities derive from the pilot geometry and manufacturing workflow. Background processes were modelled in SimaPro using Ecoinvent v3 (allocation cut-off) system model datasets [18]. At prototype stage, core inputs are represented via transparent proxies reported explicitly in the inventory: lignocellulosic substrate (straw proxy), nutrient additive (dry-milling flour proxy), and inoculum (organic grain production proxy).

Manufacturing electricity was modelled using a European medium-voltage electricity mix and treated as a sensitivity variable to reflect uncertainty in drying/deactivation requirements (low/medium/high), while baseline electricity accounts for CNC cutting

only. The conventional insulation baseline was modelled using Ecoinvent "polystyrene foam slab for perimeter insulation" as a proxy for XPS-type insulation.

Results are sensitive to the choice of conventional insulation dataset; the baseline is therefore interpreted within the uncertainty of early-stage modelling rather than as a definitive product declaration. Results are reported as (i) comparative GWP100 fossil between Hybrid (H) and Baseline (B) (Table 2, Fig. 4) and (ii) a contribution analysis for hotspot identification (Table 3).

Table 2. Comparative results (GWP100 fossil, kg CO_2-eq per FU).

Scenario	Hybrid (H)	Baseline (B)
Low drying	11.003	14.696
Mid drying	12.312	14.696
High drying	14.276	14.696

Table 3. Contribution analysis for Hybrid (H), mid scenario (IPCC 2021 GWP100 fossil), highlighting dominant drivers and sensitivity parameters.

Contributor	Hybrid (mid)	Baseline
Plywood	8.64	8.64
Electricity (MV)	2.13	0.16
Conventional insulation (polystyrene foam slab, perimeter)	–	5.89
Inoculum proxy	0.76	–
Flour proxy	0.68	–
Substrate proxy	0.10	–
Total	**12.31**	**14.70**

Overall, the screening shows that plywood production dominates the embodied impacts, while drying/deactivation electricity is the main sensitivity driving the variation across scenarios. This supports the use of screening LCA as a decision-support tool to identify hotspots and prioritize primary data collection (process energy and yields) before industrial scaling.

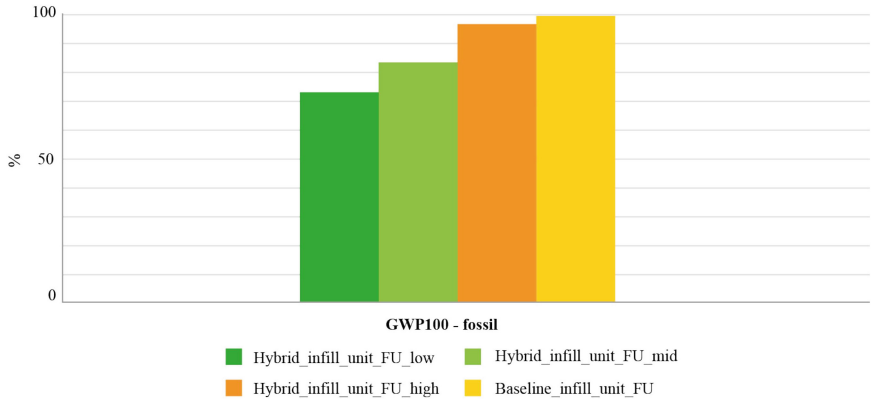


Fig. 4. Comparative GWP100 fossil results (A1–A3) for Hybrid (H) and Baseline (B), including drying-energy sensitivity (low/mid/high). Method: IPCC 2021 GWP100 V1.03

5 Conclusion and Future Work

This study proposes a timber–mycelium hybrid box-based infill unit combining CNC-fabricated plywood joinery with a bio-fabricated mycelium composite core, designed for dry assembly and selective replacement within circular construction logics [2]. The screening LCA (A1–A3) shows that plywood production dominates embodied impacts, while drying/deactivation electricity is the main sensitivity driver, consistent with mycelium-composite LCA evidence [14]. Future work will prioritize primary data collection for process energy and yields and extend the assessment through scenario-based modelling of end-of-life and reuse pathways beyond cradle-to-gate to support scale-up. Overall, integrating CNC timber fabrication, bio-fabrication and early-stage LCA provides a transferable workflow for evidence-based development of bio-based building components under circular construction strategies.

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The Effect of Wood Rheology on Reusability of Timber Products

Petr Hradil[1](✉), Stefania Fortino[1], Sabina Huč[2], Francesco Mirko Massaro[3], Haris Stamatopoulos[3], Martina Sciomenta[4], and Massimo Fragiacomo[4]

[1] VTT Technical Research Centre of Finland Ltd., Espoo, Finland
petr.hradil@vtt.fi
[2] University of Ljubljana, Ljubljana, Slovenia
[3] Norwegian University of Science and Technology, Trondheim, Norway
[4] University of L'Aquila, L'Aquila, Italy

Abstract. The long-term performance of structural timber products is strongly influenced by time-dependent phenomena such as creep and stress relaxation due to moisture fluctuations, temperature variations, and sustained mechanical loading. This performance determines the service life of such products and directly affects their reusability potential after the building disassembly at the end of its design life. Components that maintain dimensional stability and mechanical integrity can be recovered, reconditioned and reused, supporting circular economy principles and reducing environmental impact. Conversely, excessive creep, relaxation or cracks caused by moisture induced stresses limit reuse potential, necessitating downcycling or energy recovery of the material. Understanding these mechanisms enables engineers to design structures for deconstruction and reuse, ensuring that timber remains a sustainable choice in modern construction. This paper discusses strategies to assess and improve reusability through accurate prediction of the structural components' service-life based on state-of-the-art finite element modelling (FEM) of hygro-thermal and mechanical behaviour of wood. The rheological model for predicting the long-term behaviour of timber members includes a description of creep and moisture-induced reversible and irreversible deformations in compression and tension in three anatomical directions and includes shear deformations. The paper demonstrates the possibilities offered by the integration of FEM results in the life cycle assessment (LCA) of the reusable timber component.

Keywords: Timber · Reuse · Finite Element Method · Service Life · Life Cycle Assessment · Circular Economy

1 Introduction

The construction sector is a major consumer of raw materials and a significant source of greenhouse gas emissions and waste [1]. To address these challenges, circular economy principles promote extending product service life and enabling reuse after building deconstruction. Reuse of structural timber usually preserves material value and embodied

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energy more effectively than recycling, but its feasibility depends on long-term mechanical behaviour under sustained loading and environmental exposure. Timber elements experience time-dependent deformations and damage accumulation, which influence their residual service life at the time of building disassembly. These effects directly determine whether it is more efficient to reuse the component, recycle it or recover as energy.

Wood rheology is therefore a key factor for circular timber construction. Viscoelastic and mechano-sorptive behaviour leads to creep, stress relaxation or accumulation, and moisture-induced deformations, particularly under variable humidity and temperature [2]. Modelling of these phenomena enables realistic prediction of long-term performance and residual service life. The service life can be integrated into the life cycle assessment, forming a basis for informed decisions about end-of-life treatment of such components. By accounting for these effects, timber structures can be designed for deconstruction and multiple life cycles (such as the example in Fig. 1), strengthening the role of timber in circular construction.

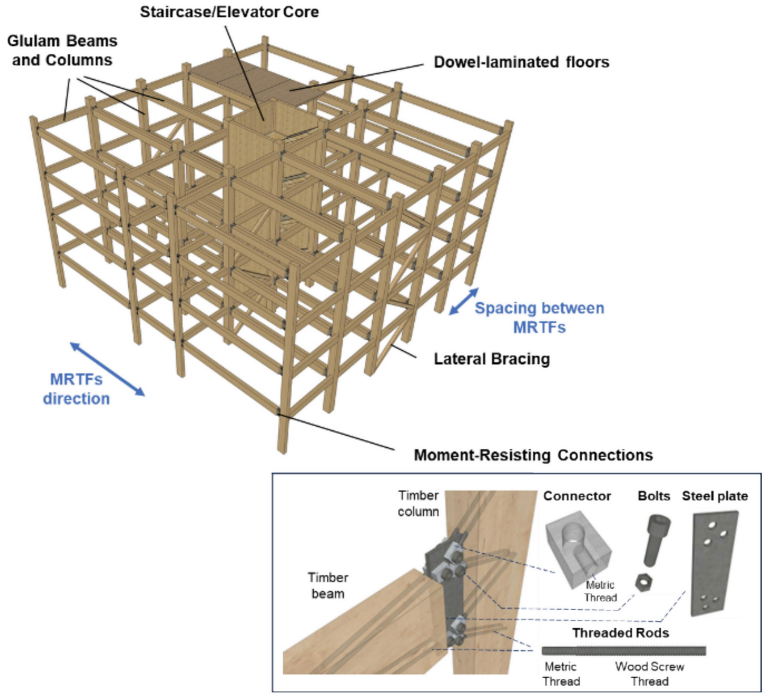


Fig. 1. Timber structure designed for deconstruction and reuse [3].

Such reusable structures are for instance timber frames with the components connected through steel coupling parts fastened to the timber elements [3]. The example in Fig. 1 shows a structural system consisting of demountable, moment-resisting connections with pre-installed steel parts in the timber elements joined with reversible, friction-based connections.

2 Methodology

This study is based on the life-cycle assessment (LCA) of a timber beam from the structural system described in Fig. 1 [3] in the building designed for 50 years, assuming the beam initially outlasts the building and can be reused after its demolition with a certain residual service life. Two scenarios are considered: (a) the beam is replaceable and reusable even if its remaining service life is shorter than the next building's design life and (b) the beam is non-replaceable and only reused if its residual service life meets or exceeds the next building's design life. The assessment focuses on the Global Warming Potential (GWP) and covers the following selected life-cycle stages according to EN 15804 and EN 15978 [4, 5]: production (LCA modules A1–3), replacement during the use (B4), deconstruction or demolition (C1), recycling or reuse (C3), and net benefits and loads from material recovery beyond the system boundary (D1).

2.1 Moisture Induced Stresses and Deformation

Long-term performance of structural timber components can be predicted using numerical simulations based on the Finite Element Modelling (FEM). The moisture content in the timber component resulting from environmental humidity and temperature variations is usually determined using a one- or two-phase moisture transport model [6, 7]. Subsequently, a mechanical model is applied to determine the long-term response of the timber component under the combined effects of external loads and moisture-induced stresses and deformations, where the total strains are assumed to be the sum of mechanical, mechano-sorptive, viscoelastic, and hygro-expansion strains [2, 8, 9]. Numerical simulations are commonly supported by experimental results that provide data for parameter calibration or model validation.

Most experimental results on the long-term performance of timber subjected to external loads and variations in humidity and temperature cover short time periods, typically less than one year [10–12]. Experimental studies covering longer time periods, i.e., up to ten years, are relatively rare [13–15]. Therefore, numerical simulations are also used to extrapolate experimental results beyond the experimentally observed time periods and estimate the performance of timber components over their service life, which may extend to several decades.

The methodology presented in this paper relies on the results obtained by FEM analysis of multi-phase moisture transport in wood [17] sequentially coupled with a mechanical model for the evaluation of internal stresses and deformations over a long period of time. This model was already used for the structural verification of load-bearing timber components of bridges [17].

2.2 Service Life Prediction

Service life can be determined from the Eurocode limit states [18], defining it as the time when time-dependent effects of actions reach the Serviceability Limit State (SLS) or Ultimate Limit State (ULS). By calculating utilisation over time and accounting for moisture-induced changes in stiffness and internal forces, the service life is identified when the utilisation reaches unity, providing a performance-based durability and reuse

assessment. This method can be in practice applied according to the illustrative FEM example presented in the earlier study [17].

The service life of structural timber components depends on the geometry of cross-sections, span lengths, connection details, material properties, and external loads (mechanical, temperature, and moisture). In the case of internal building structures with controlled temperature and humidity (Eurocode Service Class 1 and 2 [19]), the service life can significantly exceed 50 years, the standard design life for buildings according to EN 1990 [18]. Accordingly, a range of 50 to 200 years is adopted in this study to reflect both the typical and extended service life scenarios for timber in these service classes.

2.3 Allocation of LCA Impacts

The unit impacts allocated directly to the product life-cycle stages A and C are presented in Table 1 as e_A and e_C parameters. These selected values fall within the typical GWP ranges of glue laminated timber frames [20] but do not represent any specific product. The effect of biogenic carbon storage always cancels out when the impacts from all life-cycle stages are aggregated and therefore is not considered. Module D1 is calculated according to the Annex E of EN 15804 [4] with index "1" for reuse and "2" for recycling, and parameters E_{VM} and E_{MR} in Table 1.

Table 1. Parameters of the LCA model.

Unit impacts and wood waste recovery parameters	GWP [kgCO_2e/t]
Production of the new component ($e_{A,\,\mathrm{new}}$, $E_{VM,\,1}$)	70
Reuse of the component ($e_{A,\,\mathrm{reuse}}$, $E_{MR,\,1}$)	10
Demolition and waste processing ($e_{C,\,demolition}$)	10
Deconstruction and preparing for reuse ($e_{C,\,deconstruction}$)	5
Substituted production of wood chips from virgin materials ($E_{VM,\,2}$)	40
Recycling wood into chips ($E_{MR,\,2}$)	20

It is assumed that the component can be completely reused, or 80% of its mass can be recycled into wood chips and the remaining 20% of its mass can be incinerated. If the component is replaceable during the design life of the building, the impacts of its production and end-of-life recovery were allocated to the use stage of the building (LCA module B4) according to the EN 15978 [5] as illustrated in Fig. 2.

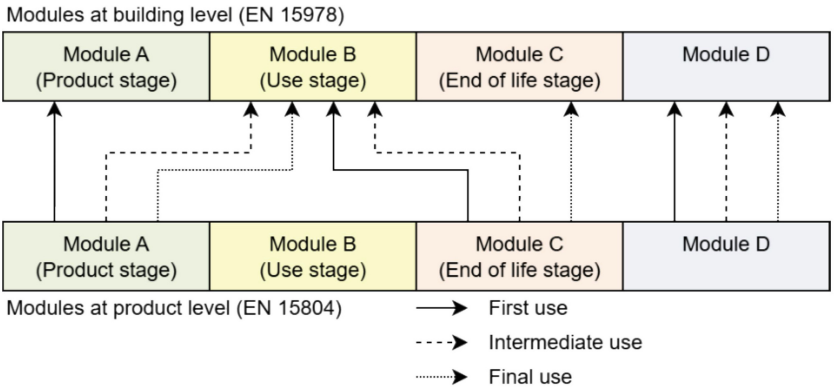


Fig. 2. Allocation of impacts from the product LCA according to EN 15978 [5].

3 Results

The average Global Warming Potential (GWP) of the component installed in one or more buildings during its service life is presented in Fig. 3 for non-replaceable component and Fig. 4 for replaceable component. Life-cycle impacts are aggregated from stages A to C, and the benefits of future reuse and recycling (module D1) are presented separately as negative values.

In the case of non-replaceable component, the results are constant for any service life of this component exceeding the design life of the building up to 50 years because such component cannot be reused anymore. If the component can be replaced, the GWP is also allocated to the use phase of the building (yellow in Fig. 4) excepting the cases when the replacement happens at the building's end of life because the residual service life of the component is equal to the multiplier of the design life of the building (for instance 100 or 150 years, or some cycles with 75 or 125 years) and the impacts are allocated to the modules A and C.



Fig. 3. Global Warming Potential of non-replaceable product in a building with 50 years of design life.

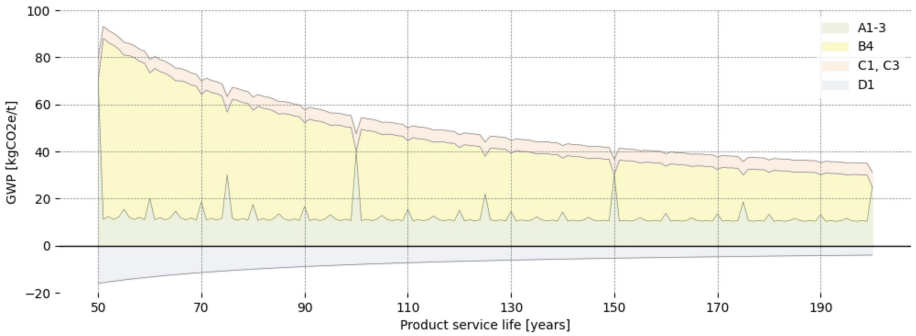


Fig. 4. Global Warming Potential of replaceable product in a building with 50 years design life considering optional product replacement at the end of building's design life.

The calculated scenarios show that in some cases it is more environmentally efficient to avoid reusing the product with short residual service life and produce the new one instead of it. Although, such cases are rare, they show the complexity of decision making at the end of the building life. In our examples, the lowest total GWP can be achieved by replacing or not replacing the product within the design life of the building depending on its service life (see Fig. 5).

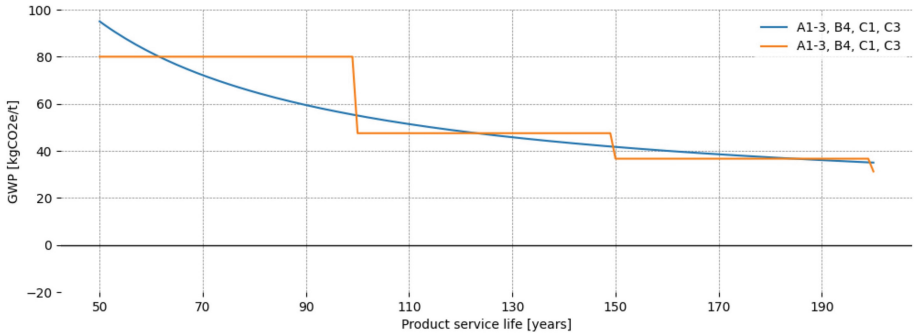


Fig. 5. Comparison of total Global Warming Potential of replaceable product (blue line) and non-replaceable product (orange line) in a building with 50 years design life.

It can be demonstrated that reuse is more environmentally efficient than recycling when the condition of formula (1) is fulfilled:

$$\left(e_{A,reuse} + e_{C,deconstruction}\right) + (nr - 1)\left(e_{A,new} + e_{C,demolition}\right) > 0 \qquad (1)$$

where the replacement rate of replaceable component $r = T_{lf}/T_{rsl}$ is the ratio of the building's design life T_{lf} and component's service life T_{rsl} defined in [18], and the number of life cycles of the non-replaceable component is $n = floor(T_{rsl}/T_{lf})$.

4 Summary and Conclusions

Long-lasting and well-designed timber structures can significantly contribute to climate-neutral and circular construction when service life of their components explicitly considered. The product manufacturers can therefore exploit the possibility to declare reference service life of their products under pre-determined conditions beyond the typical design life of the building.

Reuse, recycling and other waste management options are usually considered in a hierarchical manner at the building's end-of-life, but the European Waste Framework Directive [21] encourages to prioritize scenarios that deliver the best overall environmental outcome even if it requires departing from this hierarchy. The present study shows that realistically determined service life of timber products can justify a specific priority based on overall environmental impacts and highlight the cases when different recovery options might be superior to reuse.

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Proposed System to Quantify Embodied Carbon in Informal Housing in Brazil

Mayara Regina Munaro[1(✉)], Camila Duelis Viana[2], Heloisa Cristina Fernandes Cordon[3], Jean Appel[4], and Yuri Mariano Carvalho[3]

[1] Academic Department of Civil Construction, Universidade Tecnológica Federal do Paraná, Curitiba, Paraná, Brazil
mayaramunaro@utfpr.edu.br
[2] Institute of Geosciences, Universidade de São Paulo, São Paulo, Brazil
[3] Polytechnic School, Universidade de São Paulo, São Paulo, Brazil
[4] Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Paraná, Brazil

Abstract. Embodied carbon has become a critical dimension of building-sector decarbonization, yet its quantification remains largely restricted to formally designed buildings with detailed documentation. In countries such as Brazil, where informal settlements constitute a significant share of the urban fabric, this methodological dependency excludes millions of dwellings from environmental accounting. This paper proposes a structured, replicable system to quantify embodied carbon in informal housing, developed through an iterative empirical process in the São Remo community, São Paulo, Brazil. The first stage tested and calibrated data-collection strategies, digital capture methods, parametric reconstruction procedures, and computational integration pathways. Mobile lidar scanning, structured field protocols, locally grounded material assumptions, BIM-based modeling, and Python automation were progressively consolidated into a coherent and scalable workflow capable of transforming undocumented geometries into structured material quantities linked to regional emission factors. The methodological architecture introduced enables informal settlements to be integrated into climate mitigation and circular-economy strategies. By bridging digital reconstruction and environmental accounting, it expands embodied carbon assessment to data-scarce urban contexts across the Global South.

Keywords: Embodied carbon · Informal housing · Building Information Modeling (BIM) · Benchmarking · Construction decarbonization

1 Introduction

The decarbonization of the built environment has become a central priority in global climate mitigation agendas. While operational emissions have historically dominated policy and research [1], embodied carbon—associated with the extraction of raw materials and the manufacturing of construction products—accounts for around 18% of global emissions related to buildings and construction [2] and has gained increasing relevance, particularly in rapidly urbanizing regions in the Global South. In Brazil, embodied

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emissions account for a substantial share of housing life-cycle impacts [3], especially in low-income contexts where operational energy demand is limited.

Despite advances in Life Cycle Assessment (LCA) methodologies and digital quantification tools, embodied carbon accounting remains restricted mainly to buildings designed for formal use, particularly in the Global North, where data availability is greater [4]. Studies in the Global South are scarce and often rely on Global North data as proxies [4], which may lead to inconsistent decision-making due to a lack of regionalization [5]. Additionally, conventional assessments depend on project documentation and standardized specifications, resources typically absent in informal settlements.

Informal settlements are residential areas developed outside formal legal and regulatory frameworks, characterized by insecure tenure, limited infrastructure, regulatory non-compliance, and predominantly self-built, incrementally expanded housing with irregular geometries and no technical documentation [6, 7]. These conditions hinder their inclusion in environmental inventories, leaving the embodied carbon of such dwellings largely unquantified because of methodological limitations. Within this spectrum of informality, slums represent the most extreme condition, where precariousness, density, and construction heterogeneity are intensified. This gap is especially critical in Brazil, where 40.8% of urban dwellings present some form of inadequacy [8], 16.39 million people live in slums [9], and self-construction remains the predominant mode of housing production [10].

This paper addresses this gap. It proposes a structured and replicable system for quantifying embodied carbon in informal housing, especially slums, developed through an empirical testing phase and subsequently consolidated into a conceptual workflow. Rather than presenting embodied carbon results, this paper focuses on the methodological architecture itself: how undocumented built reality can be transformed into structured environmental data in a consistent and scalable way.

2 Research Design

The research design is structured as a circular-iterative process aimed at bridging the gap between standardized embodied carbon accounting and the complexities of informal urban environments. The study was conducted in two major phases: an exploratory-operational phase dedicated to testing data-collection and computational-modeling pathways, followed by a conceptual-consolidative phase that formalized these procedures into a replicable workflow.

2.1 Case Study Selection and Site Characterization

Following the logic of an instrumental case study [11], this research utilized multiple sources of evidence to investigate contemporary phenomena within their real-world context. The empirical focus was the São Remo slum in the western part of the city of São Paulo, Brazil—a settlement of approximately 3,000 dwellings that serves as a representative laboratory for Brazilian informal urbanization [12].

The site exhibits key characteristics of self-construction, including incremental verticalization and self-construction logic, absence of formal technical documentation,

and varied levels of consolidation and finishing [12]. To ensure structural diversity, 39 dwellings were selected based on location, height, degree of consolidation, and material finishing. Rather than a mere application site, the community functioned as a methodological laboratory where tools and assumptions were iteratively refined.

2.2 Methodological Macro-Stages

The investigation was organized into five distinct macro-stages, providing a systematic approach to quantifying embodied carbon in data-scarce environments: 1) Preparation: Definition of parameters and preliminary site assessment; 2) Data Collection: Empirical gathering of physical and material data; 3) Processing: Technical analysis and carbon quantification; 4) Methodological Proposal: Final synthesis and workflow formalization; and 5) Model Revision: Adjustments and updates to ensure the replicability of the method in other locations.

To ensure technical consistency, all analytical stages underwent internal validation cycles through peer review within the research group. This study is integrated into the Research Network MORE: Well-being and Low Carbon in Housing (https://hubic.org.br/rede-more/), a collaborative initiative focused on measuring CO_2 emissions in the housing sector. The network's broader objective is to support the transition to a low-carbon economy while aligning climate mitigation with human well-being and evidence-based public policy.

3 First Stage: Methodological Testing and Operational Calibration

The first stage aimed to determine how embodied carbon could be quantified in the absence of formal documentation. This required reconstructing quantities directly from built reality. Multiple tools and approaches were tested before arriving at the final procedure.

During Preparation, initial exploratory visits assessed urban morphology, accessibility constraints, façade conditions, and feasibility, including interior measurements. Different geometric capture methods were evaluated in Data Collection, including terrestrial laser scanning (TLS), digital photogrammetry, mobile lidar applications, and traditional laser tape measurement. While TLS offered high precision, its cost and operational complexity limited scalability. Photogrammetry demonstrated significant potential, particularly through residents' participatory data collection, which could democratize the documentation process. However, the method remained sensitive to lighting conditions and image quality, especially in cluttered interiors. Ultimately, mobile lidar, supplemented by laser tape validation for larger spans, was identified as the most viable compromise between accuracy, data richness, cost-effectiveness, and replicability. A dedicated application was developed to systematically store and structure the data collected for each dwelling.

Simultaneously, semi-structured interviews with local masons were conducted to understand typical concrete and mortar compositions, construction sequences, and decision-making processes. These interviews were essential for defining realistic material assumptions, particularly regarding cement consumption. A calculation protocol was

developed to translate informal mix descriptions into standardized mass-based ratios suitable for integration with emission factors.

For Processing, point clouds obtained through mobile scanning were converted into parametric BIM models. Digital reconstruction exposed limitations in structural visibility, wall thickness measurement, and slab composition identification. To address these gaps, technical assumptions were formulated based on local construction practices and Brazilian standards. These assumptions were progressively refined as additional dwellings were modeled. Simultaneously, early iterations exposed inconsistencies in naming conventions, parameter assignment, and quantity tables. A BIM Execution Plan and a dedicated template were therefore developed and calibrated through the first 10 models, which served as stabilization exercises. Once consolidated, the template ensured standardized outputs compatible with automated data processing.

After digital modeling, the quantities of five material groups—ceramic tiles, clay bricks, concrete, mortar, and reinforcing steel—were extracted, and their embodied carbon was calculated using Brazilian data from the Information System for Environmental Performance in Construction (Sidac) [13] or international environmental product declarations (EPD). These materials account for 82% of the global warming potential (GWP) of a standard Brazilian social housing unit [3].

The final component involved computational integration. Manual processing of BIM outputs identified operational risks, prompting the implementation of Python scripts to automate data cleaning, emission factor integration, and aggregation. This step consolidated a reproducible pipeline linking undocumented geometry to emission-based material quantification.

4 Second Stage: Consolidation of the Conceptual Workflow

The second stage consolidated the tested procedures into a coherent, sequential framework (Fig. 1). The workflow begins with preparation and standardized field data collection, combining digital capture with structured metadata registration. It advances to parametric reconstruction within a stabilized BIM environment, where locally grounded technical assumptions are embedded explicitly. Material quantities are then extracted in a structured format that enables automated integration of emission factors and calculation of indicators. The method's review is necessary to ensure its replicability in other locations, in accordance with local construction and cultural characteristics.

Rather than relying on any single tool, the robustness of the framework derives from the coordination between its components: field protocol, parametric modeling rules, emission-factor hierarchy, and computational automation. This alignment transforms fragmented and undocumented geometries into consistent datasets suitable for environmental assessment.

The modular architecture allows for regional recalibration through material substitution, adapting the workflow to quantify alternative local bio-based materials or industrial by-products; data elasticity, as the "multisource" approach makes it resilient to varying levels of technological access; and adjustment of input assumptions, enabling refinement of parametric models and embodied carbon estimates for the housing units. By

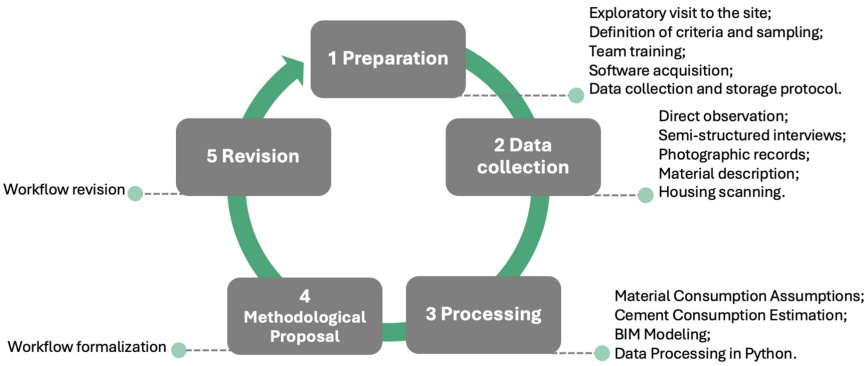


Fig. 1. Conceptual workflow to estimate embodied carbon in informal housing.

identifying material-intensive patterns, it also supports incremental upgrading strategies to improve environmental performance and housing quality, while informing circular-economy policies tailored to the metabolic flows of informal settlements.

In this way, informal housing is translated from undocumented built reality into structured environmental information through a transparent and auditable process (Fig. 2). The framework is scalable due to its operational simplicity, reproducible through explicit parameterization, and transferable because its logic remains stable even when regional assumptions or material datasets are modified.

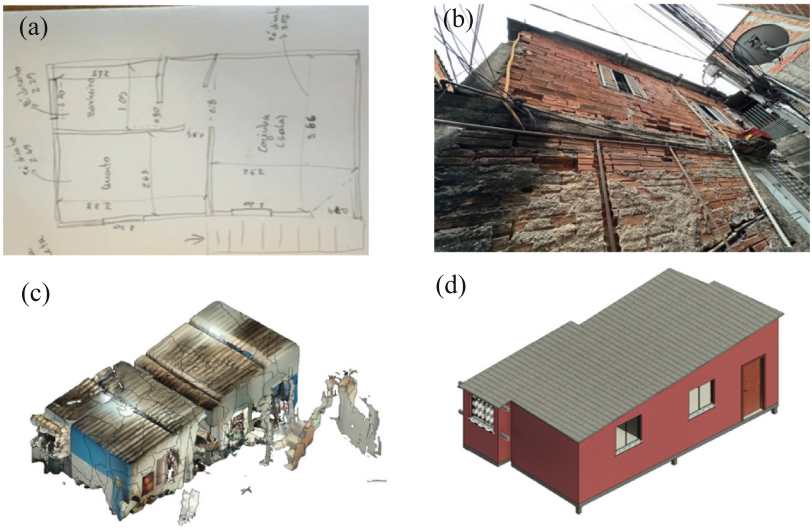


Fig. 2. (a) Example of a hand-drawn sketch surveyed from a second-floor dwelling; (b) External photograph of the dwelling; (c) 3D model resulting from the housing's 3D scanning; (d) 3D model of the housing generated in BIM (Revit 2026).

5 Implications and Limitations

By enabling embodied carbon quantification in informal settlements, this framework expands the scope of environmental accounting to territories traditionally excluded from global climate mitigation strategies. This inclusion is technically and ethically critical, as informal housing constitutes the primary mode of urban expansion across the Global South. The methodology moves beyond site-specific observation to offer a scalable diagnostic tool for regions with similar socio-technical profiles.

The methodology acknowledges unavoidable uncertainties inherent in self-construction, such as digital capture distortions and structural invisibility (e.g., hidden reinforcements). However, rather than viewing uncertainty as a barrier, the framework treats it as a quantifiable parameter. By documenting assumptions and applying carbon emission factors within defined ranges, the model ensures that the resulting baselines are both transparent and technically robust.

Future research will focus on revising the model (step 5) and expanding the sample size across diverse geographical latitudes to establish regional embodied carbon baselines. Additionally, conducting sensitivity analyses on the most volatile parameters will further stabilize the workflow for global implementation.

6 Conclusions

This research established a robust methodological framework for quantifying embodied carbon in informal housing, bridging the gap between undocumented built environments and formal environmental accounting. By integrating site-specific data, local knowledge, 3D scanning, Building Information Modeling (BIM), and Python-based automation, the study demonstrated the technical viability of transforming the morphological complexity of self-constructed settlements into structured, auditable data.

The core contribution lies in a circular-iterative workflow that standardizes quantification criteria across heterogeneous constructions, ensuring data traceability despite the absence of original technical documentation. The application in the São Remo community demonstrated that carbon estimation in data-scarce contexts depends on a coherent protocol that aligns high-tech acquisition with local empirical insights.

The framework offers high adaptive potential for other contexts in the Global South. Its modular design allows for recalibration based on local emission factors and construction techniques, providing the analytical foundation for incremental upgrading strategies. Ultimately, this study demonstrates that informal settlements—often excluded from conventional inventories—can be integrated into climate mitigation strategies, underscoring the need to align spatial justice with carbon neutrality in the transition to a low-carbon economy.

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Circularity of Compressed Earth Blocks Containing Additives: A Case Study

Jessica Ernst[1](✉), Larissa Daube[2], and Robert Brünjes[1]

[1] Biberach University of Applied Sciences, Karlstraße 9, 88400 Biberach, Germany
jessica.ernst@hochschule-bc.de
[2] Bauhaus-Universität Weimar, Belvederer Alle 1, 99425 Weimar, Germany

Abstract. The use of resource-efficient and circular building materials is gaining increasing relevance in sustainable construction. Compressed earth blocks (CEBs) represent a promising alternative to CO_2-intensive materials such as concrete due to their low embodied energy and potential recyclability. To improve mechanical performance, earthen materials are often stabilised with hydraulic binders or bio-based additives. However, the implications of such stabilisation for recyclability and environmental performance remain insufficiently understood. This study investigates the influence of different additives on the compressive strength, recyclability, and environmental impact of CEBs. The investigated additives include hydraulic binders and bio-based stabilisers. After initial mechanical testing, the fractured specimens were crushed, reprocessed, and remanufactured to evaluate strength retention after one recycling cycle. The results show that additive selection plays a crucial role for both the mechanical performance and recyclability of the material. At the same time, the stabilisation mechanism strongly influences strength retention after recycling. A screening life cycle assessment further highlights that the choice of additives can also significantly affect the environmental impact of compressed earth blocks. The findings highlight the importance of balancing mechanical performance, recyclability, and environmental impact when developing stabilised earthen materials for circular construction.

Keywords: Compressed Earth Blocks · Additives · Circular construction materials · Reuse potential · Mechanical performance · Recycling methods

1 Introduction

The transition towards circular construction requires building materials that combine structural performance with recyclability and low environmental impact. Reinforced concrete, while structurally efficient, is associated with high embodied carbon and limited material recovery. Compressed earth blocks (CEBs) offer a promising alternative due to their low embodied energy, the regional availability of raw materials and potential for full recyclability. To enhance mechanical performance, CEBs are often stabilised with hydraulic binders or bio-based additives. While such additives can significantly increase compressive strength, they may affect recyclability and long-term circular performance.

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In particular, hydraulic binders involve irreversible chemical reactions, raising questions about strength retention after recycling. It can be hypothesised that hydraulic binders provide superior initial strength, whereas natural additives may perform more favourably after reprocessing.

This study investigates the circularity of stabilised CEBs (SCEBs) by analysing the influence of selected additives on compressive strength, strength development after one recycling cycle, and environmental implications compared with conventional construction materials. The investigated additives include hydraulic binders (cement and calcium hydroxide), bio-based stabilisers (ammonium lignosulfonate, sodium alginate in combination with calcium chloride, xanthan gum, and methyl cellulose), as well as a proprietary mineral-based mixture (Oxabrick LOKO). The results contribute to the development of structurally reliable and circular earthen building systems.

The paper builds on the activities of the WG *Forschung* within the *Dachverband Lehm e.V.*, co-financed by the InDeckLe-Project (PAN-HAW-BW, 2684995).

2 State of the Art

Earthen materials are widely regarded as fully recyclable. Yet robust evidence for the recyclability of compressed earth blocks (CEBs), and for the associated changes in mechanical performance, remains limited, particularly for formulations containing different types of additives. Although additives can improve properties such as compressive strength, they may adversely affect vapour adsorption behaviour [1, 2], increase the carbon footprint, and compromise circularity [3–5].

3 Methods

Material and Composition. The clay fraction is approx. 13%, with illite identified as the predominant clay mineral. Prior to further processing, the material was homogenised in a compulsory mixer (Eirich) for 120 s at 1500 rpm with controlled water addition to ensure uniform particle distribution and moisture content.

As shown in Table 1, nine material series with different stabilising additives were produced. Series 1 served as the reference without any additives. Additive contents are expressed as mass percentages relative to the dry mass of the earthen material.

Manufacturing. After the homogenisation process, the fresh material was immediately stored in airtight containers for 14 days to allow uniform moisture redistribution, while minimising moisture loss. For specimen production, 700 g of the prepared material were placed into a cylindrical steel mould (Ø: 66.5 mm). For each series, four specimens were produced. Compaction was performed uniaxially using a universal testing machine (Zwick). The compaction regime was defined in two stages: an initial pre-compaction load of 20 kN at a loading rate of 10 kN/min, followed by main compaction at 30 kN/min up to a maximum load of 100 kN. The maximum load was maintained for 120 s to further enhance structural densification. After unloading, the specimens were immediately ejected from the mould and subsequently weighed. Conditioning was performed under ambient laboratory conditions, with the specimens drying at room temperature (T =

Table 1. Composition of the material mixture.

Serial No.	Additive	Earth [g]	Water [g]	Additive [g]	Total weight [g]	Additive [wt.%]	Water [wt.%]
1	Reference sample	2793.6	406.4	0	3200	0	12.7
2	Ammonium lignosulfonate	2744.0	399.2	56.8	3200	2.1	12.2
3	Sodium alginate + Calcium chloride	2721.7	395.9	41.2 41.2	3200	1.5 1.5	12.6
4	Xanthan gum	2768.8	402.8	28.4	3200	1.0	12.2
5	Cement (CEM I)	2687.6	431.5	80.9	3200	3.0	12.9
6	Cement (CEM I)	2543.7	466.2	190.8	3201	7.5	14.1
7	Hydrated lime	2723.0	396.1	80.9	3200	3.0	12.0
8	Methyl cellulose	2768.8	402.8	28.4	3200	1.0	12.0
9	Oxabrick LOKO	2768.8	402.8	28.4	3200	1.0	12.0

17.0 ± 8.2 °C) for more than four weeks to minimise effects related to ongoing cement hydration. Due to time constraints, the recycled specimens were additionally dried in an oven at 30 °C for 24 h. Mass loss was recorded at regular intervals. Drying was continued until mass change were less than 0.1% within 48 h. The moisture content was determined gravimetrically. Compressive testing was performed after reaching moisture equilibrium.

Testing. Uniaxial compression tests were conducted under controlled loading rate. The load was initially applied up to 100 N at a rate of 100–150 N/s. Subsequently, the loading rate was increased to 350–500 N/s and continued until specimen failure. These loading rates were selected based on the expected material strength to ensure that failure occurred within approx. 90 s. The maximum applied load ($F_{\max}$) was continuously recorded, and the compressive strength (σ_c) was calculated according to Eq. (1), where A_0 represents the initial cross-section area. Failure was defined as a 30% drop in load, ensuring consistent and reproducible identification of the material-specific failure point. Statistical evaluation of compressive strength was based on the calculated failure stresses.

$$F_{max}/A_0 = \sigma_c \tag{1}$$

Recycling. The fractured specimens from each series were collected and pre-crushed manually, and further comminuted using a jaw crusher. The moisture content of the crushed material was determined gravimetrically and deionised water was added to restore the original moisture content of each respective series. Then new specimens were similarly manufactured as before. Due to material losses during processing, only three specimens per series were manufactured and tested in this recycling cycle.

Life Cycle Assessment. A screening LCA was conducted to contextualise the environmental impact of SCEBs. The assessment focuses on Global Warming Potential (GWP) as the primary indicator, expressed in kg CO_2-equivalents (kg CO_2-eq). GWP is particularly relevant for construction materials, as production and binder-related processes contribute significantly to embodied emissions. The system boundary was defined as modules A1-A3, covering raw material supply, transport, and manufacturing.

Environmental data were obtained from established databases and environmental product declarations (EPDs). GWP values for the investigated additives and binders were sourced from ÖKOBAUDAT [6, 7] and CarbonCloud [8–11], supplemented where necessary by literature data [12, 13]. These datasets were used to quantify the climate impact contribution of each additive relative to the earthen matrix and to compare SCEBs with conventional construction materials.

For the CEBs, GWP values were derived from the UPD dataset [9]. As the dataset reports impacts per unit mass, block-specific GWP values were calculated based on a dry density of 2060 kg/m^3. The dataset assumes industrial drying using natural gas, although sun drying may be applied in practice for economic reasons.

Additive contents were defined as wt.% of the dry earth mass. Mixture-specific GWP values were obtained by multiplying component masses with their database-derived GWP factors and summing the contributions.

To contextualise the findings, the resulting GWP values were compared with typical ranges for conventional mineral construction materials, including fired clay bricks, concrete, and calcium silicate bricks, using the same data sources. This comparison enables assessment of whether strength enhancements through additives remain compatible with low-carbon and circular construction objectives.

4 Results

4.1 Effect of Additives on Compressive Strength

Figure 1 shows the mean compressive strength for the investigated material series before and after recycling.

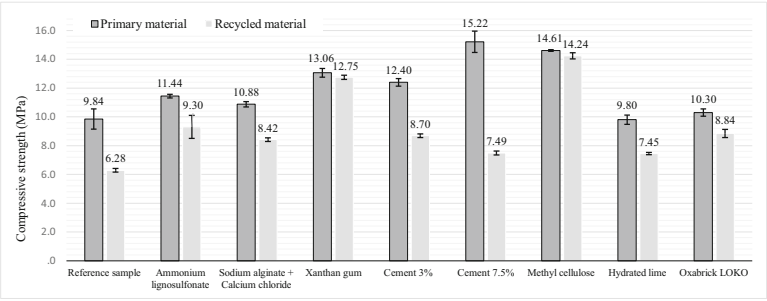


Fig. 1. Compressive strength of primary and recycled (S)CEBs with marked standard deviation.

The additive-free reference mixture reached a mean compressive strength of 9.84 MPa. Among the investigated additives, only hydrated lime led to a slight reduction in strength relative to the reference. All other formulations showed higher compressive strengths, with the highest values measured for 7.5% cement (15.22 MPa) and 1.0% methyl cellulose (14.61 MPa).

4.2 Effect of Recycling on Compressive Strength

Figure 1 also compares the compressive strength of the primary and recycled material. Remarkably, none of the series recovered its initial compressive strength after recycling. The highest strength retention was observed xanthan gum and methyl cellulose, which retained 97.6% and 97.5% of their initial strength, respectively. By contrast, the series containing 7.5% cement, showed the lowest retention reaching only 49.2% of its initial compressive strength. The reference series retained 63.8% of its initial compressive strength. The corresponding percentages are summarised in Table 2. In addition, the water content and dry density of the specimens at the time of compressive strength testing are also reported for both the primary material (1) and the recycled material (2). The dimensions of the specimens were height: (1) 91.6 mm ± 1.1 mm Ø: 65.8 mm ± 0.2 mm; (2) 92.6 mm ± 2.1 mm Ø: 65.9 mm ± 0.4 mm.

Table 2. Material properties and relative compressive strength of primary and recycled SCEBs.

Additive	Water content (1) [wt.%]	Water content (2) [wt.%]	Dry density* (1) [kg/m^3]	Dry density* (2) [kg/m^3]	Relative compressive strength (%)
Reference sample	2.4	1.9	2063	2057	64
Ammonium lignosulfonate	2.1	1.9	2049	2063	81
Sodium alginate + Calcium chloride	2.8	2.9	2071	2070	77
Xanthan gum	2.1	2.1	2056	2073	98
Cement (CEM I)	2.0	2.0	2044	2018	70
Cement (CEM I)	2.4	2.5	2047	1961	49
Hydrated lime	2.0	1.8	2039	2022	76
Methyl cellulose	2.1	2.0	2038	2038	97
Oxabrick LOKO	2.3	2.1	2077	2091	86

* The dry density refers to the moisture equilibrium state of the specimens at the respective water content reported in the table. The water content was determined gravimetrically by taking a material sample immediately after the compression test and oven-drying it at 105 °C.

4.3 Life Cycle Assessment of the Investigated Additives

The LCA reveal that the investigated additives can substantially increase the production-related CO_2 emissions of CEBs (see Fig. 2).

The reference sample exhibits a GWP of 113.7 kgCO_2-eq/m^3, mainly caused by artificial drying [13]. The addition of Oxabrick® LOKO increases this value moderately by 19% to 134.8 kgCO_2-eq/m^3 [14].

In contrast, mixtures containing sodium alginate and calcium chloride show a drastic increase, reaching 815.4 kgCO_2-eq/m^3, corresponding to more than 600% above the

reference [10, 11]. This effect is primarily driven by the high GWP of sodium alginate (21.3 kg CO_2-eq/kg). Approximately 63% of these emissions originate from seaweed cultivation, including aquaculture, harvesting, transport of wet bio-mass, and fertiliser production, while 35% result from energy-intensive processing steps such as extraction, precipitation, filtration, and drying [11].

Other additives also lead to notable increases in GWP. The addition of 1.0 wt.% xanthan gum raises emissions by approx. 140% [9], while mixtures containing 2.1 wt.% lignosulfonate or 7.5 wt.% cement increase the GWP by slightly more than 90% [6, 12]. Due to the lack of dedicated datasets, sodium lignosulfonate production was used as a proxy. Smaller but still significant increases were observed for hydrated lime (3.0 wt.%; GWP +58%), methyl cellulose (1.0 wt.%; GWP +54.6%), and cement (3.0 wt.-%; GWP +36.5%) [6–8].

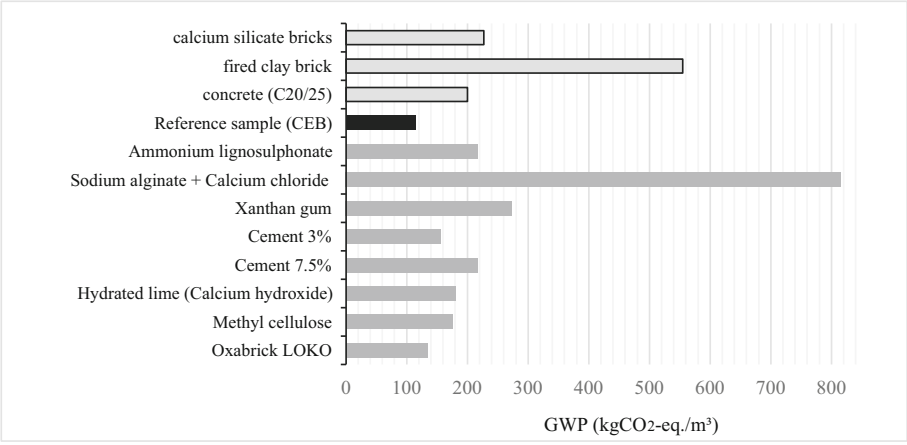


Fig. 2. Comparison of the GWP (A1–A3) of SCEBs listed in Table 1 with conventional construction materials (calcium silicate bricks, fired clay bricks, and concrete), based on [6–17].

However, compared with conventional mineral building materials (calcium silicate bricks, fired clay bricks, and concrete C20/25), most mixtures still exhibited lower GWP values. Among the conventional materials, concrete shows the lowest footprint, with approx. 200 kgCO_2-eq/m^3 [15]. Compared with concrete, only the mixtures containing hydrated lime (GWP –10.2%), methyl cellulose (GWP -12.2%), and cement (3.0 wt.%; GWP –22.4%) achieved lower GWP values.

In contrast, the mixture containing xanthan gum performed worse than calcium silicate bricks, while the combination of sodium alginate and calcium chloride even exceeded the GWP of fired clay bricks by 46.9% [16, 17].

5 Discussion

While most investigated additives increased compressive strength (av. +2.4 MPa), their incorporation consistently led to a substantial increase in carbon footprint, with GWP rising by an average of 136%. Only hydrated lime led to a slight reduction in compressive strength (−0.4%), while increasing the CO_2-footprint by 58%.

Notably, the reference sample showed a large decrease in compressive strength after recycling (−36%). A possible explanation may be insufficient mixture homogeneity, which should be investigated in further experiments.

The addition of cement, hydrated lime, sodium alginate combined with calcium chloride, and ammonium lignosulfonate significantly impaired the performance of the recycled material, resulting in an average reduction in compressive strength of approx. 3.7 MPa after recycling, which may be partly attributed to the relatively high additive dosage ($\geq$2.1 wt.%). This behaviour could also be explained by the irreversible hydration reactions of hydraulic binders during the first production cycle, which limits their contribution to strength development after reprocessing. Similar trends have been reported by Audren et al. [3]. Moreover, the combination of sodium alginate and calcium chloride increased the GWP by approx. 600%.

However, the addition of xanthan gum or methyl cellulose resulted in a considerably smaller reduction in compressive strength after the first recycling process, with an average decrease of only 0.34 MPa. In both cases, the additive dosage was only 1.0 wt.%, which further supports the assumption that additive content plays a decisive role in this effect. In contrast, the addition of 1.0 wt.% Oxabrick LOKO did not lead to a similar behaviour, as the compressive strength decreased by 1.46 MPa after recycling. However, an increase in the number of recycling cycles could further enhance the observed effects.

6 Conclusion

The results suggest that CEBs are difficult to recycle due to their high compaction. Given the low environmental impact ambition of these materials, the selection of stabilising additives needs a careful elaboration and targeted research on efficient recycling and processing methods is required. Methyl cellulose and xanthan gum showed high strength retention, suggesting that such additives can facilitate the loosening of the grain structure at the particle level and thereby improve the recyclability of the material. Overall, the results demonstrate that even small amounts of additives can considerably alter the environmental performance of SCEBs.

The study is limited to a single recycling cycle and compressive strength testing. Further research should assess repeated recycling, durability-related properties, alternative processing strategies, a additive reintroduction during recycling and the effect of dosage. It should also be noted that the results are based on a small-scale laboratory investigation; therefore, further studies under larger-scale or practical conditions are necessary to confirm the findings.

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Environment-Carbon-Energy Relationships to Justify Climate-Responsive Economic, Technical and Nature-Based Solutions

Irina Kolupaieva(✉) and Yurii Romashov

Kharkiv National University of Radio Electronics, Nauky Ave. 14, 61166 Kharkiv, Ukraine
iryna.kolupaieva@nure.ua

Abstract. This study examines relationships between environmental indicators, carbon dioxide (CO_2) emissions from economic activities, and existing energy technologies to justify climate-responsive economic, technological, and nature-based solutions. The research purposes to develop qualitative representations of environment–carbon–energy relationships using mathematical tools and available statistical data. The methodology combines mathematical modeling and statistical analysis of environmental, energy, and emissions indicators, allowing identification of key dependencies between conditions, emissions, and energy systems. Results show that environment–carbon–energy relationships can be represented through qualitative models. The analysis highlights integrated climate measures, including reforestation, biotechnologies for high-carbon-sequestration plants, improved energy technologies, and reduced energy use, which may reduce CO_2 emissions and mitigate environmental degradation. The approach provides a basis for preliminary assessments and supports future research and policy development.

Keywords: Carbon-Dioxide · Energy · Production · Consumption · Environmental Resilience

1 Introduction

Rising atmospheric carbon dioxide (CO_2) concentrations are a major driver of global climate change, highlighting the need for climate-responsive solutions. Effective strategies should combine economic measures, technological improvements, and nature-based restoration to reduce environmental degradation. Because CO_2 emissions are largely energy-related, it is essential to analyze environment–carbon–energy interactions for understanding human impacts and informing policy development [1].

Environment–carbon–energy interactions differ across countries due to variations in economic development, technological capacity, and natural resources. Studies show that both developed and emerging economies face significant challenges related to carbon emissions and environmental pollution. Addressing these challenges requires coordinated international efforts and evidence-based policies that balance economic development with environmental sustainability. The increasing availability of environmental

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and economic data enables the application of advanced computational methods to analyze these relationships. This research develops models that support climate-responsive economic, technological, and nature-based solutions for sustainable environmental management.

1.1 A Literature Review

Rising atmospheric carbon dioxide (CO_2), largely driven by economic activity, is a major contributor to global climate change. Because most emissions are energy-related, research increasingly focuses on environment–carbon–energy interactions [2]. These relationships differ across countries due to variations in economic development and technological capacity. However, all economies face similar challenges related to carbon emissions and environmental pollution [3, 4]. Addressing this global issue requires coordinated international action and sustainable policy frameworks [5, 6]. Mathematical methods are widely used to analyze these interactions and support evidence-based environmental policies aimed at reducing CO_2 emissions [2–4, 7].

1.2 A Principal Goal and Research Questions

This research focuses on the relationships between environmental, energy, and carbon dioxide (CO_2) emission indicators, which are essential for supporting climate-responsive economic, technical, and nature-based solutions. The principal objective of this study is to develop general qualitative representations of environment–carbon–energy relationships.

To achieve this objective, the research addresses the following research questions (RQs):

RQ1: How can environment–carbon–energy relationships be represented using mathematical tools and existing statistical data?
RQ2: Which economic, technical, and nature-based solutions can be implemented to support climate-responsive policies?
RQ3: What are the expected effects of implementing climate-responsive solutions?

The results of this research are intended to provide a conceptual framework that can be used other researchers for further analysis and policy development.

2 Methodology

The methodology of this research applies mathematical modelling and statistical analysis to examine the relationships between environmental indicators, carbon dioxide (CO_2) emissions from economic activities, and existing energy technologies. Using available statistical data, the study develops qualitative representations of environment–carbon–energy interactions. This approach enables the assessment of environmental responsibility within current energy systems and supports the evaluation of economic, technological, and nature-based solutions aimed at reducing emissions and improving environmental performance.

2.1 A Natural Environment

Influence of carbon dioxide emissions related to economic activities on the natural environment is considered through the by using the following ordinary differential equation:

$$dx/dt = -a(t)x + mE(t), \tag{1}$$

where $x = x(t)$ is the carbon dioxide concentration above the natural value depending on the time t; $a(t)$ is the integrated absorption parameter; $E(t)$ is the carbon dioxide emission related to all economic activities; m is the coefficient required to transform the mass of the carbon dioxide to its concentration.

The proposed Eq. (1) is indeed simplified Lotka-Volterra equations considering atmospheric carbon dioxide as the prey, but plants and other dioxide carbon absorbents as the predators, so that the simplification is due to representing the predators by means of the integrated absorption parameter depending on the time. The existing statistical data represent the carbon dioxide concentration and emission during the time, and they allow us to estimate the integrated absorption parameter:

$$t = t_k,\ \ x_k = x(t_k),\ \ E_k = E(t_k)\ \ \Rightarrow\ \ a_k = (mE_k - dx_k/dt)/x_k,\ \ k = 1, 2, \ldots, n, , \tag{2}$$

where t_k is the year associated with known statistical data x_k and E_k; $a_k = a(t_k)$ is the estimated value for the integrated absorption parameter at the time t_k; dx_k/dt is the derivative approximately computed through x_k values using well-known 3-nodes formulas; n is the count of available statistical data.

The values a_k estimated using Eq. (2) and the existed statistical data about forests' area allow us to make parametric identification to estimate the relationship:

$$a = \alpha F, \quad \alpha = \sum_{k=1}^{n} a_k F_k / \sum_{k=1}^{n} F_k^2, \tag{3}$$

where α is the parameter of the linear regression between the absorption parameter a and the forests' area F; F_k is the known forests' area related to the t_k year.

Thus, Eqs. (1) and (3) allow us to represent the influences of carbon dioxide emissions and deforestation on the carbon dioxide concentration.

2.2 Economics and Energy Technologies

The carbon dioxide emissions are economic activities requiring energy usages, so the energy consumption can be assumed as the economic indicator. The production of energy required to be consumed is responsible for carbon dioxide emissions, so this emission is depended on the energy consumption:

$$E = \beta C, \quad \beta = \sum_{k=1}^{n} E_k C_k / \sum_{k=1}^{n} C_k^2, \tag{4}$$

where β is the parameter of the linear regression between the carbon dioxide emission E and the energy consumption C; C_k is the energy consumption at the t_k year.

The value β defined by the Eq. (4) gives the carbon dioxide emission per unit of consumed energy, so environment-responsible energy technologies must provide smaller value of this value. Thus, this value, defined by Eq. (4), represents the overall level of environmental responsibility of energy technologies.

2.3 Climate-Responsive Solutions

An increase in atmospheric carbon dioxide (CO_2) concentration is a critical driver of climate change, making it essential for climate-responsive solutions to focus on preventing further rises. The Eq. (1) allows us to define:

$$dx/dt = 0 \Rightarrow -a(t)x(t) + E(t) = 0 \Rightarrow E(t) = a(t)x(t). \tag{5}$$

Substitutions of Eqs. (3) and (4) to Eq. (5) lead to the following relationship providing zero velocity of carbon dioxide concentration:

$$C = F\alpha x/\beta. \tag{6}$$

The Eq. (6) gibes the environment-responsible energy consumption (economic activity) providing zero velocity of carbon dioxide concentration for its already achieved concentration x and for the existing forests' area F under the existing level β of energy technologies and the and nature's ability α to absorb carbon dioxide.

3 Primary Data, Results, and Discussions

The Internet resources provides data on climate, biodiversity, and economic activity, enabling analysis of environment–carbon–human interactions. Databases from international and government sources support modeling and scenario analysis, helping to assess trends and guide climate-responsive policies.

3.1 Carbon Dioxide

Research on carbon dioxide (CO_2) is based on multiple data sources. Concentration data are obtained from the Copernicus Climate Change Service (C3S) [8], supported by the European Union. Total CO_2 emissions data are sourced from the World Bank's Open Data portal, Data360 [9], while emissions from energy combustion and industrial processes are provided by the International Energy Agency (IEA) [10]. These datasets form the empirical basis for analyzing environment–carbon–energy relationships and assessing climate-responsive solutions. The data [8, 9] are given in the tabled view, but the data from the site [10] are extracted manually from the corresponding diagram; all the data are collected in the single xlsx file. The data [8] are given for month periods, and they are averaged for calendar years. So, these accessible data provide primary quantitative estimations using Eqs. (2) and (5).

The coefficient m, which was introduced in Eq. (1), is defined in the view:

$$m = 10^{12}10^6/V, \quad V = \frac{4}{3}\pi(R+h)^3 - \frac{4}{3}\pi R^3, \quad R = 6371000 \text{ m}, \quad h = 10000 \text{ m}, \tag{7}$$

where m is the coefficient that allows us transform Gt to mg/m^3; V is the volume of the atmosphere's part containing the most of the carbon dioxide; R is the radius of the Earth, and h is the height of the atmosphere's part containing the most of the carbon dioxide.

Corresponding programs were developed using the R programming language and the related Anaconda open-source software to perform calculations and visualize the results, as shown in Fig. 1.

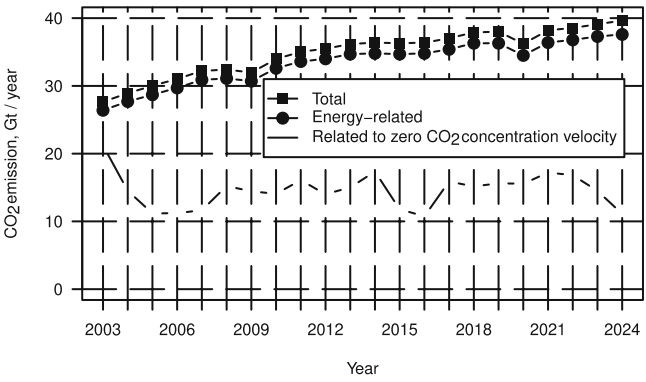


Fig. 1. Carbone dioxide emissions.

Analysis of the primary data and computed results indicates that the majority of carbon dioxide (CO_2) emissions are energy-related, and overall CO_2 emissions have increased over time. Actual CO_2 emissions exceed the computed values corresponding to a zero velocity of CO_2 concentration (see Fig. 1), indicating that current emissions contribute to a rise in atmospheric CO_2 levels. The difference between actual emissions and those corresponding to zero velocity was relatively small in 2003 (approximately 30%) but increased substantially by 2014 (approximately 300%), despite the total increase in CO_2 emissions from 2003 to 2014 being only about 30%. This discrepancy is attributed to a twofold decrease in the CO_2 emissions corresponding to zero velocity of concentration during this period (see Fig. 1). Therefore, the increase in CO_2 concentration results not only from rising emissions but also from the decline in the reference emission level corresponding to zero velocity. Reducing CO_2 emissions to the 2003 level has a mitigating effect but does not fundamentally alter the trajectory of environmental pollution.

3.2 Influences of Deforestation and Energy Technologies

Research on the influences of deforestation and energy technologies is based on data from the World Bank's Open Data portal [11, 12]. Data [11] are provided in tabular

form, while data [12] were manually extracted from the corresponding diagram. All data were consolidated into a single XLSX file. These datasets, together with results computed using Eq. (5), provide primary quantitative estimations through Eqs. (3) and (4). Corresponding programs were developed using the R programming language and related open-source software to perform calculations and visualize the results, as shown in Fig. 2.

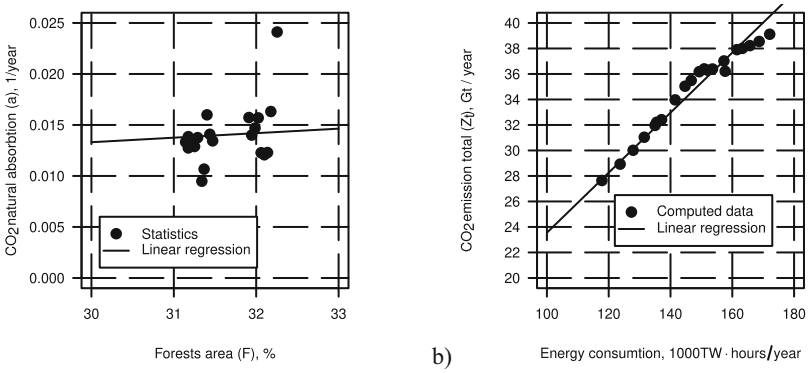


Fig. 2. Estimations for deforestation (a) and energy technologies (b)

Figure 2 a demonstrates that deforestation significantly influences the CO_2 absorption capacity. The linear regression model (Eq. 3) approximates the actual data reasonably well (see Fig. 2a), indicating that forest area is not the sole factor determining CO_2 absorption. Nevertheless, the regression model can be used for preliminary estimations of absorption capacity and provides a basis for further analysis.

The results (see Fig. 2b) show that the linear regression Eq. (4) allows us represent relationships between a carbon dioxide emission and an energy consumption. It proves, that energy technologies are the same during the times covered by the data.

3.3 Environment-Carbon-Energy Relationships

The results presented in Figs. 1 and 2 allow the application of Eq. (6), which is illustrated in Fig. 3 using programs developed in the R programming language and related open-source software for calculations and visualization.

As shown in Fig. 3, actual carbon emissions are approximately twice the values corresponding to zero velocity of CO_2 concentration, indicating that reducing emissions alone is insufficient to prevent environmental degradation. However, increasing forest cover from 31% to 33% and improving energy technologies to achieve a 50% reduction in carbon emissions, combined with reducing energy consumption to 2003 levels, can help prevent further environmental degradation.

It should be emphasized that CO_2 absorption capacity, as defined in Eq. (1), can be enhanced not only through reforestation but also by selecting plant species with higher carbon sequestration potential.

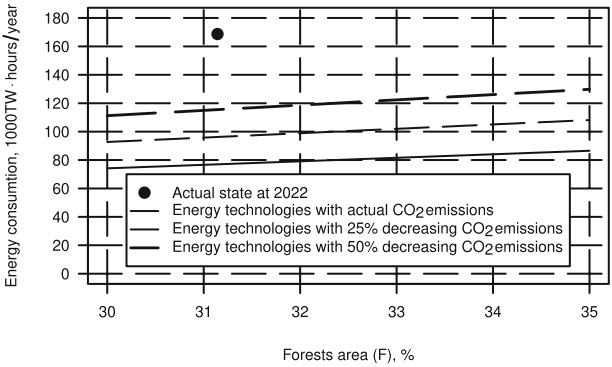


Fig. 3. Carbon dioxide emissions related to zero velocity of carbon dioxide concentration (curves) and an actual state (marker).

4 Conclusions

This study examined relationships between environmental indicators, CO_2 emissions, and energy technologies to support climate-responsive solutions. Results indicate that environment–carbon–energy interactions can be represented qualitatively using mathematical tools and statistical data, highlighting key links between environmental conditions, emissions, and energy systems. The findings emphasize the importance of integrated climate measures. Reforestation, biotechnologies for high-carbon-sequestration plants, improved energy technologies, and reduced energy use can help lower CO_2 emissions, mitigate environmental degradation, and support more effective environmental and energy policies. Despite these contributions, the study is limited by focusing mainly on forest area, with other environmental and ecological factors not fully incorporated. Future research should include additional environmental indicators and factors affecting carbon absorption, as well as more detailed statistical analysis and expanded datasets for more precise assessment of environment–carbon–energy relationships.

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Integrating Circular Economy Principles into Industrialized Façade Renovation Systems: A Multi-KPI Assessment

Magdalena Zabek[1(✉)] and Thaleia Konstantinou[2]

[1] Chair of Resource-efficient Construction, TU Dortmund University, 44227 Dortmund, Germany
magdalena.zabek@tu-dortmund.de
[2] Department of Architectural Engineering, TU Delft University, 2628 BZ Delft, Netherlands

Abstract. This study investigates how circular economy principles can be integrated into industrialized building envelope renovation systems to reduce environmental impacts and support the EU's climate neutrality targets. In the context of a real-world façade renovation scenario, a multi-KPI methodology is applied to assess resource efficiency and sustainability across four European demonstration buildings. The approach combines the hierarchical alignment of Key Performance Indicators (KPIs) - particularly Global Warming Potential (GWP), reuse, recycling, and biobased content—with decision-making analyses that link material choices to quantifiable environmental effects. An assembly-level assessments support transparency in design decisions and highlight the influence of stakeholder engagement, regulatory constraints, and economic considerations. Results show significant variability in GWP across façade systems, largely driven by structural materials such as steel and aluminium, while biobased insulation contributes notable carbon reductions. The comparison of the façade renovation solutions with alternative material strategies demonstrates the potential for lower-carbon renovation systems through increased use of timber structures, biobased composites, and recycled materials. The study concludes that early integration of sustainability expertise and KPI-driven design processes is essential to achieving resource-efficient, low-carbon renovation outcomes, providing a practical roadmap for advancing circularity in the built environment.

Keywords: circular renovation · industrialized façade systems · life cycle assessment · KPIs · Global Warming Potential · circular economy

1 Introduction

The Circular Economy (CE) promotes resource efficiency by narrowing, slowing, and closing material loops [1]. Standardized methods such as Life Cycle Assessment (LCA) and the Level(s) methodology [2], provide a framework for assessing carbon emissions and resource consumption in the built environment.

Achieving climate neutrality by 2050 [3] requires decarbonization, resource efficiency, and large-scale renovation. Over 85% of European buildings fail to meet energy

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efficiency standards [4]. While deep renovations can cut energy consumption by 60–90% [5], the current renovation rate is insufficient [4]. The EU Renovation Wave [4] aims to double energy-based renovations by 2030 to accelerate progress. By 2027, life-cycle Global Warming Potential (GWP) calculations will be mandatory for construction projects [6], emphasizing the need for circular renovation strategies.

A shift from traditional to industrialized renovation systems is crucial to achieving efficiency and sustainability. Prefabricated solutions enhance speed, reduce disruption, and allow for modular adaptability. This study examines circularity considerations in developing an industrialized building envelope renovation system of a real case scenario [7] (illustrated in Fig. 1).

The study adopts a multi-KPI (Key Performance Indicator) approach, structured as follows:

- Hierarchical alignment of KPIs, aligning LCA [8, 9] and Level(s) framework [2] with common CE definitions.
- Decision-making impact assessment, linking design choices to environmental KPIs such as GWP.
- Assembly-level evaluation, providing granular insights into the environmental performance of a modular system and alternative solutions.

Analyzing building systems at the assembly level is crucial, as it allows design solutions and research findings to be transferred across projects due to their scalability and applicability to diverse construction contexts. The present research aims to support sustainable renovation practices by providing transferable strategies that enable measurable environmental benefits.

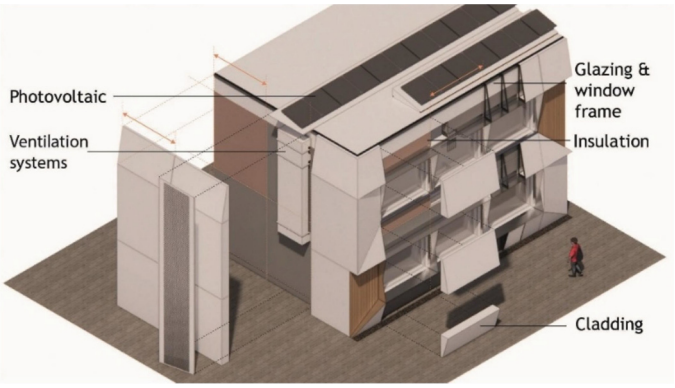


Fig. 1 AEGIR façade system. Image courtesy of AEGIR project partner UNStudio

2 Methodology

The approach of the study targets the hierarchical alignment of a multiple-KPI perspective based on the following consideration:

- Identification and hierarchical alignment of KPI's (Sect. 3),
- Linking decisions to environmental effects and KPIs (Sect. 4), and
- Assessment at the Assembly-Level and proposing alternative solutions (Sect. 5).

The decision making is implemented in the renovation design and evaluation of 4 demo cases presented in Table 1.

Table 1. Overview of AEGIR demo buildings

	Demo 1	Demo 2	Demo 3	Demo 4
Photo				
Location	Denmark (DK)	Spain (SP)	France (FR)	Romania (RO)
Description	Social housing	Educational building	Residential home for elderly people	Residential building

3 Identification and Hierarchical Alignment of KPI's

KPIs guide design processes toward circularity. In the AEGIR project [7] and related studies [10–12] KPIs inform decisions on material reuse, lifespan extension, and modularity, supporting sustainability. They align with the European CE strategy and the UN 2030 Agenda [13], particularly SDG 12.

CE concepts, such as Cradle-to-Cradle (C2C) [14] and the R-strategies [15], emphasize continuous material flows and biodegradability. KPIs based on these models include material purity, recyclability and the use of renewable or biobased materials. Standard tools like LCA and Level(s) quantify environmental impacts, focusing on GWP and circularity [2]. Within the study framework, GWP and the amount of secondary resources were prioritized as KPIs, with biobased materials lowering GWP and secondary materials reducing resource extraction.

4 Linking Decisions to Environmental Effects and KPI's

As product selection plays a critical role in determining the future reusability, resource efficiency, and environmental impact of materials and components [16–18], the prioritized KPIs guided the decision-making process.

Environmentally responsible product selection requires comprehensive data collection at both component and material levels across multiple functional categories. Therefore, during the early design stages, a material database was developed to store all relevant product information, including quantitative data on the selected KPI's.

Architects, who significantly shape material choices and construction methods, often struggle to make environmentally responsible decisions [19] due to a lack of clear guidelines and the absence of harmonized benchmarks [20]. This highlights the crucial role of

sustainability experts in guiding the decision-making process toward environmentally friendly solutions.

4.1 Decision-Making in the AEGIR Project

In the AEGIR project, sustainability experts shaped decisions by evaluating products' GWP (Sect. 5) and fostering stakeholder collaboration. Across all demos, outcomes reflected the complex interplay of design, sustainability, and stakeholder interests, with regulatory, social, and financial factors strongly influencing decisions. The following sections outline stakeholder roles and key factors affecting sustainability and other project decisions.

4.2 Stakeholder Involvement

Across all demo projects, the involvement of sustainability experts proved to be pivotal. They played a key role in conducting LCA, advising on secondary materials, and guiding strategies for material preservation. A recurring challenge, however, was ensuring that sustainability considerations were integrated early enough in the process, as well as managing the additional costs associated with circularity strategies.

The Danish demo project highlighted the importance of clear and early communication between experts and building owners. Guidance from advisory bodies at an early stage was essential, particularly in conveying circularity principles to owners. This proved critical when economic concerns initially led to the project's rejection, demonstrating that informed dialogue can shift perspectives and enable more sustainable decisions.

Similarly, the Spanish demo project underscored the value of engaged ownership combined with early involvement of sustainability experts. This collaboration helped ensure that reused materials met both environmental performance requirements and availability constraints. Despite practical challenges, proactive engagement from the owner ultimately strengthened the project outcomes.

In the Romanian project, early involvement of contractors enabled greater flexibility in integrating circular materials and adapting construction processes accordingly. Nevertheless, the lack of stakeholders representing the end-of-life (EoL) phase limited opportunities for component reuse, pointing to the need for a more comprehensive inclusion of actors across the entire building lifecycle.

4.3 Sustainability Decisions in the Demonstration Projects

In the Danish demo, an early material inventory enabled the identification of reusable components, supporting material recovery and embodied carbon reduction, with ceramic tiles selected based on GWP and structural feasibility. The Spanish demo emphasized reclaimed eucalyptus wood for cladding to enhance durability and reduce carbon emissions, while also assessing laminated biobased panels for their GWP performance. In the French demo, low-carbon concrete was initially considered but ultimately replaced by aluminium cladding due to regulatory and weight constraints. In the Romanian demo, the owner's preference for virgin materials limited circular strategies, shifting the focus toward energy efficiency and influencing thermal performance decisions.

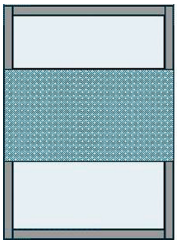
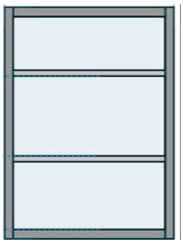
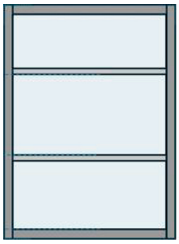
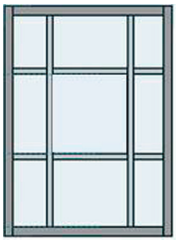
4.4 Other Influencing Factors

The French project illustrated how innovation is often constrained by timelines and approval processes. Lengthy regulatory procedures and concerns regarding material performance ultimately led to a shift from low-carbon concrete to conventional aluminum cladding. More broadly, decision making throughout the project was strongly shaped by regulatory and practical constraints, including weight limitations, structural requirements, fire regulations and approval timelines. In addition, cost considerations played a decisive role, with economic factors significantly influencing the final selection of materials.

5 Assessment at the Assembly Level

This study assesses the GWP (kg CO_2 eq.) of opaque façade modules used in the AEGIR demonstration projects. The system consists of modular units incorporating structural elements, internal and external enclosures, gaskets for airtightness, and insulation and cladding for thermal performance. The results are presented in Table 2.

Table 2 Assessment of the GWP (CO_2 eq.) of each AEGIR opaque panel

	Demo 1 (DK)	Demo 2 (SP)	Demo 3 (FR)	Demo 4 (RO)
				
Total Area	6.23 m^2	9.03 m^2	6.408 m^2	4.72 m^2
Technology	PV panels	/	/	2 Vents
Structure GWP	Aluminum 89.1	Steel 17.9	Wood -14.2	Steel 113.4
Anchorage GWP	Steel 0.2	Steel 0.1	Steel 0.3	Steel 9.7
Cladding GWP	Ceramic tiles 7.3	Ceramic tiles 1.5	Aluminum 51.5	Ceramic tiles 7.3
Insulation GWP	Woodfibre -8.4	Woodfibre -7.9	Woodfibre 7.7	Woodfibre -10.8
Enclosure GWP	Fiber cement 9.8	Fiber cement 9.8	Fiber cement 4.9	Fiber cement 9.8
PV panel GWP	28.5	/	/	/

(*continued*)

Table 2 (*continued*)

	Demo 1 (DK)	Demo 2 (SP)	Demo 3 (FR)	Demo 4 (RO)
Total GWP/m^2	**96.4**	**36.3**	**38**	**155.4**

The environmental performance of the façade systems varies considerably across the demo sites. The Danish system shows a GWP of 96.4, largely driven by the aluminium structure, which accounts for 62% of the total, while wood fibre insulation offsets emissions by 6%.

The Spanish system achieves a substantially lower GWP, supported by biogenic materials. Wood fibre insulation provides a reduction of 15%, while the steel key frame contributes to a total of 35% GWP.

The Romanian system records the highest GWP at 155.4, dominated by its steel structure, which accounts for 66% (113.4 GWP).

The French solution achieves the second-lowest GWP at 38, largely due to timber structures, which provide a reduction of 27%. However, windows and metal shading systems significantly increase the overall impact, accounting for 57% of the total GWP.

5.1 Development of Alternative Solutions

The AEGIR solution relies on steel and aluminium for structural components. While durable and recyclable, these materials have a high GWP due to energy-intensive production. Lower-carbon alternatives include Cross-Laminated Timber (CLT) or recycled steel and aluminium. For cladding, AEGIR uses ceramic tiles, aluminium sheets, or laminated biobased panels, which range from moderate to high GWP. Alternatives such as timber cladding, bio-based composites with improved EoL systems, or low-carbon concrete could significantly reduce emissions if recycling challenges are addressed. Biobased insulation materials like wood fibre or cellulose help offset emissions through carbon sequestration but require careful consideration of fire safety and EoL strategies. Alternatives include hempcrete or straw as biodegradable options, or recycled PET and fabric insulation, although these represent downcycling; upcycling should be prioritized.

Metal shading systems substantially increase GWP. Lower-impact alternatives include smart windows or fabric shading systems with better recyclability.

Finally, photovoltaic panels help offset embodied emissions over time, while metal-based ventilation systems contribute to GWP but are not included in the calculations. Thin-film photovoltaics, bio-based ventilation components, or manual ventilation systems could further reduce the overall environmental impact.

6 Conclusions

This study shows that industrialized building envelope renovation systems can significantly reduce environmental impacts when circular economy principles are embedded in early design decisions. Using a multi-KPI framework aligned with LCA and the Level(s) methodology, GWP and secondary resource use proved effective in guiding material selection toward circular solutions.

Results from the four AEGIR demonstration projects highlight that environmental performance is strongly influenced by structural systems, material choices, and stakeholder involvement. Biogenic materials consistently lowered GWP through carbon sequestration, while steel and aluminium structures dominated embodied emissions. Early involvement of sustainability experts supported informed decision-making, whereas regulatory constraints, costs, and limited end-of-life stakeholder integration often restricted circular options.

Assembly-level assessments revealed that structures, windows, and shading systems are key GWP drivers. The analysis of alternative solutions indicates further reduction potential through timber-based or recycled materials, improved EoL strategies, and lower-impact façade and energy systems.

Overall, the findings confirm that KPI-driven, industrialized renovation approaches can deliver measurable environmental benefits and support upcoming mandatory life-cycle assessments, while highlighting the need to address regulatory and process barriers to scale circular renovation practices.

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Environmental Impact of Building Technical Systems: Readiness and Challenges of the Industry

Pablo Hernandez-Cruz[1](✉), Ricardo Mateus[2], Ivan Flores-Abascal[1], and Juan María Hidalgo-Betazos[3]

[1] ENEDI Research Group, Department of Energy Engineering, University of the Basque Country (UPV/EHU), Plaza Torres Quevedo 1, 48013 Bilbao, Spain
pablo.hernandezd@ehu.eus

[2] Department of Civil Engineering, University of Minho, ISISE, ARISE, Campus de Azurém, Guimarães 4800-058, Portugal

[3] ENEDI Research Group, Department of Energy Engineering, University of the Basque Country (UPV/EHU), Nieves Cano 12, 01006 Araba, Spain

Abstract. Achieving global emission-reduction targets in the building sector requires not only the construction of nearly Zero Energy Buildings and the renovation of existing stock, but also a rigorous assessment of the environmental impact and embodied carbon of these interventions. Life Cycle Assessment is the standardised methodology for quantifying such impacts, while Environmental Product Declarations (EPD) provide third-party verified information at the product level. To date, industry efforts have been focused on passive building components, such as insulation, windows, and façade systems. However, within the nZEB framework, Heating, Ventilation, and Air Conditioning (HVAC) systems, such as heat pumps, mechanical ventilation, or photovoltaics, play a crucial role in achieving decarbonisation. Despite this, their environmental impact remains insufficiently characterised. This study reviews the currently available data for assessing HVAC systems, including Life Cycle Inventory databases, EPD repositories, scientific literature, and a survey of manufacturers. The results show that the sector is not yet prepared to consistently quantify these impacts. The main barriers identified are the lack of regulatory requirements and the technical complexity associated with developing EPDs.

Keywords: Life Cycle Assessment · Environmental Product Declaration · Heating, Ventilation and Air Conditioning

1 Introduction

The concept of planetary boundaries, introduced by Rockström et al. [1], defines the environmental limits within which human activities can safely operate. Several of these limits have already been exceeded, threatening the stability of global socio-economic systems [2]. In this context, buildings play a major role, accounting between 30 and

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40% of global energy use and Greenhouse Gas (GHG) emissions [3]. Beyond climate change, the built environment also contributes to other environmental pressures, including water use, resource depletion, ozone depletion, acidification, eutrophication, and waste generation throughout the life cycle of construction products [4].

To comprehensively assess these impacts, Life Cycle Assessment has emerged as a key methodology. Standardised under ISO 14040 and ISO 14044, LCA evaluates the environmental impacts of a process or product across all its life cycle stages, from raw material extraction to end-of-life. A critical stage of the LCA is the Life Cycle Inventory (LCI), which consists of the systematic compilation and quantification of all relevant input and output flows of a product system throughout its life cycle. Additionally, in the European construction sector, LCA is formalised through standards such as EN 15978 for buildings and EN 15804 + A2 for Environmental Product Declarations (EPDs), which provide verified and comparable product-level data. These standards also establish harmonized system boundaries, impact categories, and reporting rules, ensuring consistency in the characterization and comparability of environmental profiles.

In recent years, LCA is evolving from a voluntary practice to a regulatory requirement. European policies such as the Energy Performance of Buildings Directive recast (EPBD, 2024) and the revised Construction Products Regulation (CPR) are driving the mandatory assessment and disclosure of life cycle environmental impacts. However, while EPDs are well established for construction materials, their development for technical systems, particularly HVAC, remains limited. This gap is mainly due to the complexity of these systems and their heavy dependency on operational conditions. Nevertheless, increasing regulatory pressure is expected to accelerate the availability of reliable environmental data for HVAC systems.

In this context, this work analyses the current state of EPD implementation within the HVAC sector and explores future trends. The study combines a review of public LCI and EPD databases together with a systematic review of LCA studies involving HVAC systems, focusing on data sources. Additionally, a survey of European HVAC manufacturers is conducted to assess the sector's readiness. This work aims to provide a comprehensive overview of current limitations and support the integration of HVAC systems into building-level LCA. Given the current scarcity and heterogeneity of publicly available HVAC environmental data, this work is intended as an exploratory state-of-practice assessment rather than a fully quantitative analysis.

2 Methodology

The three foundational aspects of this work are: an exploration of available data in public LCI and EPD databases; a systematic review of scientific studies on LCA, including HVAC systems; and a questionnaire for HVAC manufacturers regarding their knowledge and readiness for EPDs of HVAC systems. Due to extension limitations, a selection of the most used systems in residential buildings has been made, including boilers, Heat Pumps (HP), Mechanical Ventilation (MV) systems, Photovoltaic (PV) panels, and Solar Thermal (ST) panels. All these systems were indistinctly differentiated both for heating and/or Domestic Hot Water (DHW) services.

2.1 LCI and EPD Databases Review

The review of LCI and EPD databases was initiated through the analysis of platform search engines such as OpenLCA Nexus (nexus.openlca.org) and Global LCA Data Access (globallcadataaccess.org). Based on these generic search tools, a total of 32 databases were identified, prioritising open-access platforms. Of these, 23 correspond to platforms collecting EPDs, while the remaining 9 provide generic LCI datasets. The geographical scope of the analysed databases is presented in Fig. 1, showing that the highest number of platforms are located in Spain, followed by Germany and Australia. Additionally, 4 of the analysed platforms have an international scope. This approach ensures a broad and globally representative dataset. For each platform, a comprehensive search was conducted to identify available environmental data for the HVAC systems previously defined. Each database was manually screened and classified according to the presence and quantity of HVAC-related datasets for the selected technologies.

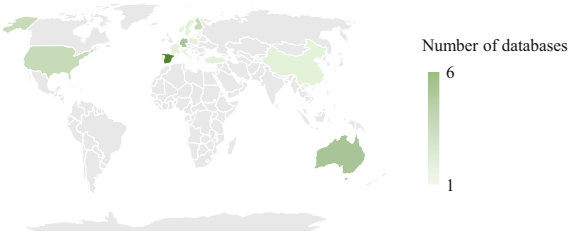


Fig. 1. Geographical scope of the LCI and EPD databases included in the review.

2.2 Scientific Literature Review

A systematic review approach was adopted for the literature analysis, using two widely used databases: Scopus and Web of Science (WoS). Due to the study's extension limitation, the search queries were strictly defined, limiting the search to studies published within the last 5 years and including keywords such as "EPD", "HVAC", or "built environment". The search has also been segmented by the type of HVAC system analyzed. For example, for boilers, the query used in Scopus is "*ALL ((“life cycle assessment”” OR LCA) AND (“environmental product declaration” OR EPD) AND (boiler* OR “natural gas boiler*”) AND (building* OR “built environment”) AND (HVAC OR “heating ventilation air conditioning”)) AND PUBYEAR > 2020*". Studies were included when they provided explicit environmental impact calculations for specific HVAC systems using identifiable LCI datasets or EPD sources. Review papers, methodological discussions, and studies without system specific inventory data were excluded from the final sample used for this study.

Figure 2 presents the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the search process. A total of 110 studies were initially identified. Most of them involve MV systems, followed by PV and HPs. After removing 37 duplicates, a screening phase based on titles, abstracts, and keywords

reduced the sample to 40 studies. Finally, eligibility criteria were applied, restricting the analysis to high-impact (Q1) journal publications. The final sample comprises 29 studies, predominantly focused on MV, PV, and HP systems, with boilers the least represented. These studies were analysed in detail, examining the HVAC systems addressed, the data sources used, and the LCA stages considered.

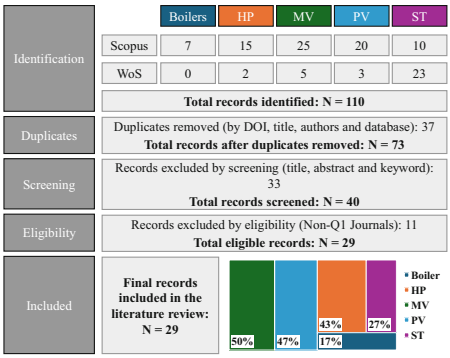


Fig. 2. PRISMA flow diagram used in the systematic review.

2.3 Questionnaire for Manufacturers

Finally, this study is supported by a questionnaire currently being distributed to HVAC system manufacturers to assess their level of awareness and readiness regarding the development of EPDs for their products. In short, the questionnaire is structured into three main sections. The first addresses general company information, including the types of HVAC systems manufactured and their geographical scope. The second focuses on the level of knowledge of LCA and EPD related regulations, as well as perceived barriers and incentives for conducting such assessments. The third directly examines whether manufacturers currently have any EPD for their products and whether they plan to develop them in the future. As the survey is still ongoing, only preliminary results are reported in this study. At this stage, the questionnaire results are considered indicative and exploratory, as the survey campaign is still ongoing.

3 Results and Discussion

3.1 Environmental Product Declarations (EPDs) Databases Review

Figure 3 presents the list of analysed EPD and LCI databases, including their geographical scope, names, and websites. For each database, the number of available items for the HVAC systems under study was assessed and categorised as follows: no items (white), at least one item (orange), between two and five items (blue), and more than five items (green). Regarding EPD databases, out of the 23 analysed, 8 contain no EPDs for the selected HVAC systems. In the remaining databases, available data are limited and highly

heterogeneous. Boilers and ST systems show the lowest data availability, whereas PV and MV systems are the most represented. From a geographical perspective, the French platform PEP Ecopassport stands out, providing more than five EPDs for each analysed system.

As for LCI databases, 7 out of 9 platforms include data related to HVAC systems. However, these are typically generic datasets rather than product-specific items, covering a range of system configurations. Notably, both the EPD and LCI databases include extensive data on passive building components, highlighting the significant gap relative to the data available for HVAC systems.

	Geographical scope	Database	Boiler	HP	MV	PV	ST
EPD	International	- Environdec (environdec.com)					
	International	- ECO Platform (eco-platform.org)					
	International	- EPD HUB (manage.epdhub.com)					
	International	- Labelling Sustainability (labelingsustainability.com)					
	Spain	- CSOSTENIBLE (csostenible.net)					
	Spain	- GBCe (materiales.gbce.es)					
	Spain	- AENOR (aenor.com)					
	Spain	- IETcc (opendap.es)					
	Germany	- ift Rosenheim (ift-rosenheim.de)					
	Germany	- Institut Bauen (ibu-epd.com)					
	Australia	- EPD Australasia (epd-australasia.com)					
	U.S.A.	- SMART EPD (smartepd.com)					
	Finland	- Rakennustieto EPDs (ymparisto.rakennustieto.fi)					
	Portugal	- DAPHabitat (daphabitat.pt)					
	Norway	- EPD Norge (digi.epd-norge.no)					
	Austria	- Bau-EPD (bau-epd.at)					
	Denmark	- EPD Denmkark (epddanmark.dk)					
	Italy	- EPD Italy (epditaly.it)					
	Poland	- ITB EPD (itb.pl)					
	France	- PEP ECO Passport (register.pep-ecopassport.org)					
	Slovenia	- ZAG EPD (zag.si)					
	Turkiye	- EPD Türkiye (epdturkey.org)					
	Ireland	- EPD Ireland (igbc.ie)					
LCI	Spain	- ITEC (itec.es)					
	Spain	- IVE (bdc.f-ive.es)					
	Germany	- OKÖBAUDAT (oekobaudat.de)					
	Australia	- University of Melbourne (msd.unimelb.edu.au)					
	Australia	- Australian LCI Database (auslci.com.au)					
	U.S.A.	- NREL LCI (lcacommons.gov)					
	Finland	- CO2 data (CO2data.fi)					
	China	- HiQLCD (hiq.earth)					
	Sweden	- Boverket (klimatdatabasen.boverket.se)					

No data available | At least 1 item available | Between 2 to 5 items available | More than 5 items available

Fig. 3. List of the EPD and LCI databases analysed and results of the accounting of identified HVAC systems.

3.2 Scientific Literature Review

The bibliographic review analysed key aspects such as geographical context, building typology, LCA system boundaries, and the specific HVAC systems considered. Attention was given to the source of LCA data, distinguishing between manufacturer-specific EPDs and generic database inputs. Of the 29 studies initially included (Fig. 2), only 13 were deemed directly relevant for detailed analysis, as they provide explicit LCA calculations for HVAC systems. The discarded studies are not relevant because they are review papers or focus on methodological frameworks without analysing specific systems or using detailed LCI or EPD data. This result itself reflects the current limited maturity and transparency of HVAC specific LCA data within the scientific literature.

Figure 4 summarises the main findings of these 13 studies selected, whose references are [5–13]. The sample is internationally distributed, although predominantly European. Most studies focus on residential and office buildings, and primarily analyse HP, PV, and MV systems, with ST being the least represented. Most adopt a cradle-to-grave

approach, although with variations regarding the modules included, particularly in the operational phase. Regarding data sources, 9 studies rely on the Ecoinvent database, while 2 use One Click LCA, both of which are proprietary tools. Only 1 study uses the French open-access PEP Ecopassport database. Additionally, 5 studies report using manufacturer-specific EPDs, mainly for PV systems, although none explicitly reference the EPDs, limiting transparency and reproducibility. It is also worth noting that all the studies analysed do include the environmental impact of the thermal envelope elements in their analyses, emphasizing that there are no availability problems with these elements.

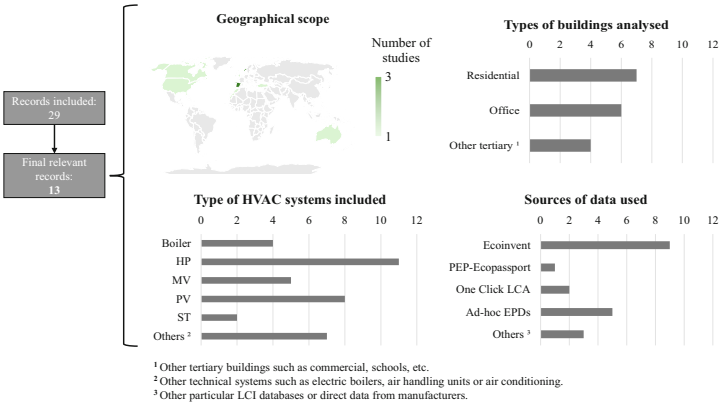


Fig. 4. Main results of the aspects analysed within the systematic review.

3.3 Discussion

The results from both the database analysis and the literature review reveal a clear lack of available data for conducting robust environmental impact assessments of HVAC systems within the building environment. Among the 29 databases analysed, only one (the French PEP Ecopassport) provides a substantial number of EPDs for multiple technical systems. Similarly, out of an initial sample of 110 studies, only 13 explicitly assess the environmental impact of HVAC systems. Although standards such as ISO 14040/44, EN 15978, and EN 15804 + A2 provide a common methodological framework, their practical implementation for HVAC systems remains inconsistent due to the limited availability of harmonized product-specific data

Several studies, Beneito et al. [5], Kayaçetin et al. [9], and Loli et al. [10], highlight this data gap, noting the difficulty of obtaining reliable, manufacturer specific EPDs. Seuntjens et al. [17] further suggest that generic data often require validation with real manufacturer data to ensure robust LCA results. At the same time, other studies, Norouzi et al. [14], Opher et al. [15], y Rabani et al. [16], indicate that HVAC systems account for an increasing share of total building impacts (between 17% and 31%) as building energy demand decreases with new construction standards. However, life cycle stages of HVAC systems such as production and end-of-life are often excluded due to their

complexity (Gobinath et al. [7]), and most studies only consider HVAC systems in operational stages. Preliminary results from the manufacturer survey confirm these findings. While respondents acknowledge the growing regulatory pressure to assess environmental impacts and develop EPDs, most indicate that they currently lack such data and have no immediate plans to produce it, mainly due to technical complexity and limited market demand.

4 Conclusions

In conclusion, this study analyses the significant gap in the availability and quality of environmental impact data for HVAC systems within the building sector. The results should be interpreted considering the limited availability and comparability of publicly accessible HVAC environmental datasets. Despite the increasing relevance of LCA in regulatory and research contexts, the results show that current data sources (both EPD repositories and LCI databases) remain limited, fragmented, and highly heterogeneous. The literature review further confirms that only a small subset of studies explicitly addresses HVAC systems using detailed and transparent datasets, with a strong reliance on private databases rather than manufacturer-specific information.

Moreover, the findings indicate that although HVAC systems are becoming increasingly important contributors to total building impacts, their embodied emissions remain insufficiently characterised, particularly beyond the operational phase. The preliminary results from the manufacturer survey reinforce this conclusion, revealing low readiness levels and highlighting key barriers, including technical complexity and limited market demand. Overall, the sector is not yet adequately prepared to consistently quantify the environmental impact of HVAC systems. As future work, further research will focus on a detailed assessment of the quality of available data, as well as expanding and consolidating the results of the manufacturer survey with a larger sample size.

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Environmental Performance of Agro-Industrial By-Products as Circular Feedstock for Building Materials: Insights from Portuguese Residues

Chiara Turco(✉), Cláudia Jacinto, Elisabete Teixeira, and Ricardo Mateus

Department of Civil Engineering, University of Minho, ISISE, ARISE, Guimarães, Portugal
chiaraturco@civil.uminho.pt

Abstract. Agro-industrial by-products are increasingly explored as circular feedstocks for sustainable construction materials. However, their environmental performance is often assumed, while assessments frequently emphasise avoided impacts from substituted products overlooking the impacts embedded in the by-products themselves. This study evaluates the environmental profiles of three Portuguese residues–wheat straw (WS), cork granules (CG), and ground olive stones (GOS)–to assess their suitability for bio-based building materials. A cradle-to-gate life-cycle assessment was conducted using one tonne of by-product as the functional unit and considering multiple impact categories, including global warming potential, acidification, fossil resource use, land occupation, and water depletion. The results reveal marked variability among commonly classified "bio-based" materials. WS and CG show net biogenic carbon sequestration, although WS presents relatively high nitrogen-related eutrophication impacts linked to agricultural practices, while CG displays exceptionally high land-use impacts associated with cork oak management. GOS shows positive carbon emissions and higher fossil resource use due to energy-intensive processing. These findings demonstrate that circular biomass utilisation should rely on accurate life-cycle assessments accounting for specific agricultural practices and regional supply chains, to support more informed material choices and eco-design strategies.

Keywords: Agro-Industrial Residues · Circular Bioeconomy · Bio-Based Materials · Environmental Impacts · Sustainability · Resource Valorisation

1 Introduction

The construction sector is responsible for substantial resource consumption, greenhouse gas emissions and waste production, making it a priority domain for advancing sustainability and circularity strategies worldwide [1, 2]. In recent years, agro-industrial by-products have attracted growing attention as potential feedstock for low-carbon, bio-based construction materials [3, 4]. Their utilisation is often presented as a mutually beneficial strategy: diverting residues from low-value or environmentally burdensome pathways while replacing emission-intensive construction materials. However, this narrative tends to assume that all biomass-derived by-products offer similar environmental benefits, overlooking the heterogeneity of agricultural systems, processing technologies and regional resource conditions [5].

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The shift from linear to circular models in construction demands more than simply identifying alternative material streams. It requires an understanding of how resource loops perform environmentally across their full life cycle, including trade-offs that may contradict the simplistic assumption that "bio-based equals sustainable". From this perspective, assessing agricultural by-products purely through carbon metrics is insufficient; a broader set of impact categories is required to understand their role within sustainable material ecosystems. Life cycle assessment (LCA) offers a robust framework for quantifying the environmental impacts of such materials and for revealing burdens that are not immediately visible from carbon metrics alone [6].

While many studies evaluate bio-based composites, insulation, or products that incorporate agricultural by-products, fewer examine the impacts of the by-products as standalone feedstock. This gap creates the implicit assumption that the upstream burdens of these residues are negligible or uniformly low, potentially leading to misguided material choices or incomplete circularity assessments. This study addresses this gap by performing a cradle-to-gate LCA of three agro-industrial by-products focusing on a comprehensive set of impact categories relevant to biomass systems, including climate change, eutrophication, acidification, fossil resource use, freshwater ecotoxicity, land occupation, and water depletion.

2 Materials and Methods

2.1 Materials and System Description

This study examines three agro-industrial by-products commonly available in the Mediterranean region: wheat straw (WS), cork granules (CG), and ground olive stones (GOS). Figure 1 shows them.



Fig. 1. Agro-industrial by-products examined: (a) WS, (b) CG, and (c) GOS.

These materials were collected in the Alentejo region, in southern Portugal, characterised by a Mediterranean climate, with hot dry summers, mild winters, and seasonal water scarcity. They were selected as they are representative of distinct biomass value chains (annual cereal agriculture, perennial agroforestry, and perennial fruit oil production) and have proven to be usable in the manufacture of bio-based materials with enhanced thermophysical properties or save raw material [7]. This variability makes them suitable case studies for analysing environmental impacts within biomass-derived resources.

Wheat Straw. WS is the fibrous residue remaining after wheat grain harvesting. In Portugal, it is typically baled directly in the field and used primarily for animal bedding, soil incorporation, or low-grade energy recovery [7, 8].

Cork Granules. CG are derived from the trimming, punching, and milling stages of cork processing. The Portuguese cork industry is globally dominant, operating within long-established cork oak agroforestry systems [9, 10].

Ground Olive Stones. GOS originate from the milling and separation phases of olive oil production. They are generated in large quantities in Mediterranean olive-growing regions. Olive stones are often valorised as biomass fuel, but their incorporation into construction materials is increasingly explored due to their hardness, lignocellulosic composition, and thermal properties [11].

2.2 Life Cycle Assessment Methodology

This study applies a cradle-to-gate LCA to quantify the environmental burdens associated with producing one tonne of WS, CG, and GOS. The methodology follows ISO 14040 standards [12], encompassing goal and scope definition, inventory analysis, impact assessment, and interpretation.

Goal and Scope. The goal of the LCA is to evaluate and compare the environmental profiles of three agro-industrial by-products commonly proposed as circular feedstock for bio-based building materials. The functional unit (FU) selected for this study is 1 t of dry by-product, defined at the point where each residue becomes available for use as a material input. The analysis focuses on upstream burdens only, excluding any downstream transformation into construction products, transportation to building sites, or end-of-life scenarios. This approach isolates the environmental characteristics of each by-product independently from any specific application, enabling generalisable insights for material selection.

Life Cycle Inventory (LCI). Inventory data for WS and CG were obtained from the Ecoinvent v3.9.1 database, while GOS were modelled using specific literature data [13]. The LCI includes impacts associated with the application of fertilisers, the use of diesel in harvesting machinery, electricity consumption in milling processes, and typical transport distances in Portuguese supply chains [13].

Allocation Procedures. Given that the selected materials are by-products with varying economic relevance, different allocation approaches were adopted, in accordance with ISO 14040 [12] and EN 15804 [14]: (i) economic allocation for processes where residues have market value (cork granules and olive stones); (ii) mass allocation for wheat straw due to its lower economic differentiation relative to grain.

Impact Assessment. For the environmental impact assessment, the following impact categories were selected: climate change (GWP), ozone depletion (ODP), acidification (AP), eutrophication (EP), photochemical ozone formation (POCP), fossil resource use (ADP), ecotoxicity (ECOTOX), land use (LU), and water use (WU).

This set covers both conventional LCA indicators and those particularly relevant to bio-based materials, such as land and water-related burdens. All characterisation calculations were performed using SimaPro v.9.5.0.0, with impact calculations performed through the life cycle impact assessment (LCIA) method.

3 Results and Discussion

The graph of Fig. 2 presents the potential environmental impacts associated with the production of one tonne of WS, CG and GOS across different categories of indicators.

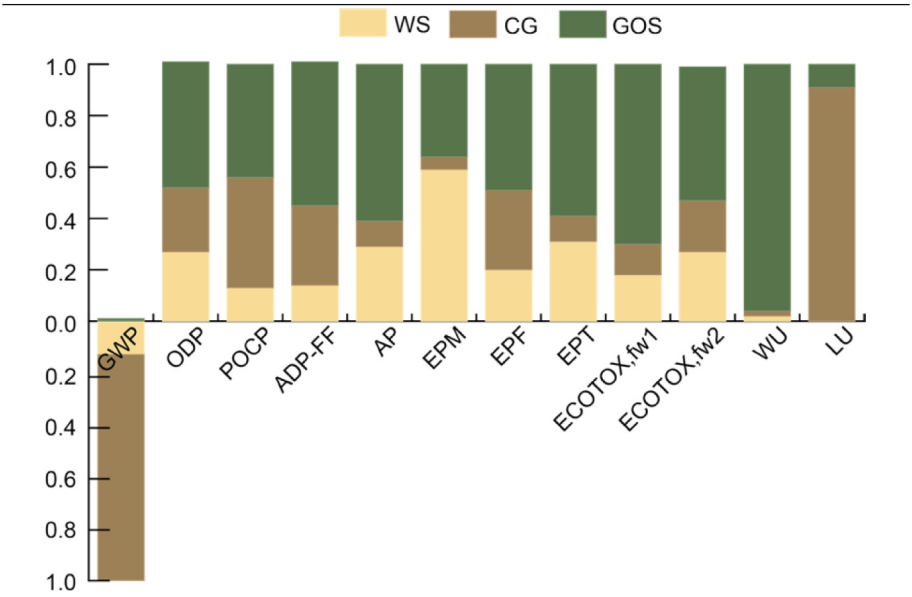
The environmental impacts associated with the production of each by-product reveal significant contrasts between the different impact categories. As for climate change indicator (GWP), the production of WS and CG exhibit negative biogenic carbon values (−200 and − 1361 kg CO_2-eq, respectively), indicating net CO_2 sequestration. CG show particularly high sequestration values because the cork oak, a tree endemic to the Iberian Peninsula, acts as a prolonged carbon sink. Stripping does not kill the tree; on the contrary, it stimulates the regeneration of cork, which enhances CO_2 fixation [15]. Conversely, the production of GOS has a positive GWP impact (21.49 kg CO_2-eq), largely due to the high demand for fossil energy used in the pulp separation process and subsequent olive milling [13]. This high energy consumption is also reflected in the fossil resource consumption indicator (ADP-FF), with GOS ranked first (1339 MJ), followed by CG (735.1 MJ) and WS (334.2 MJ).

Acidification (AP) and eutrophication (EP) are mainly influenced by field management practices. WS has the highest potential for marine eutrophication (EP-M: 1.20 kg N-eq), while GOS has the greatest impacts on acidification (AP: 1.56 mol H + -eq), terrestrial eutrophication (EP-T: 6.13 mol N-eq) and freshwater eutrophication (EP-F: 0.029 kg P-eq), reflecting the intensive use of nitrogen and phosphate fertilisers in its cultivation. CG generally has lower values for these indicators, as the cork oak is a forest species that rarely receives intensive fertilisation.

Regarding POCP, the higher values for GOS (0.647 kg NMVOC-eq) and CG (0.631 kg NMVOC-eq) are linked to the industrial processing stage, specifically thermal treatments and grinding, which release volatile precursors. This is particularly relevant in the Mediterranean summer, where high solar radiation catalyses ozone formation from machinery exhaust and industrial emissions. ODP impacts remained negligible across all materials, though GOS (2.12E-06 kg CFC11-eq) showed a slight increase due to its higher fossil energy demand and associated upstream chemical processes.

The impacts on $ECOTOX_{fw1\&2}$ vary greatly between residues. Notably, GOS exhibits a significantly higher ecotoxicity impact compared to the others natural by-products, as this correlates with the use of pesticides and herbicides in olive grove soil management and with emissions of volatile organic compounds during industrial olive processing. WS, although also treated, has a shorter growth cycle and, in many cases, a lower pesticide load per tonne of biomass than intensive olive cultivation.

Finally, a considerable impact is associated to often overlooked but relevant categories, such as water and land use. In terms of WU, producing one tonne of GOS requires a substantial 552.2 m^3, mainly related to the intensive irrigation of modern olive groves. This figure is critical, given that water scarcity is severe in the Mediterranean region.



Legend: EI = Environmental Impact; GWP = Global Warming Potential; AP = Acidification Potential; EP-M, -F & -T = Eutrophication Potential Marine, -Freshwater & -Terrestrial; POCP = Photochemical Ozone Creation Potential; ODP = Ozone Depletion Potential; ADP-FF = Abiotic Depletion Potential of Fossil Fuels; $ECOTOX_{fw1\&2}$ = Ecotoxicity, freshwater – Part 1 (organics chemicals) & 2 (metals/inorganics); WU = Water Use; LU = Land Use.

EI category	Unit	WS	CG	GOS
GWP	kg CO_2-eq	–2.00E+02	–1.36E+03	2.15E+01
ODP	kg CFC11-eq	1.16E-06	1.08E-06	2.12E-06
POCP	kg NMVOC-eq	1.95E-01	6.31E-01	6.47E-01
ADP-FF	MJ	3.34E+02	7.35E+02	1.34E+03
AP	mol H+-eq	7.43E-01	2.52E-01	1.56E+00
EP-M	kg N-eq	1.20E+00	1.04E-01	7.36E-01
EP-F	kg P-eq	1.17E-02	1.82E-02	2.87E-02
EP-T	mol N-eq	3.19E+00	1.06E+00	6.13E+00
$ECOTOX_{fw,1}$	CTUe	4.34E+02	2.92E+02	1.70E+03
$ECOTOX_{fw,2}$	CTUe	1.70E+02	1.27E+02	3.24E+02
WU	m^3 depriv.	1.38E+01	9.06E+00	5.52E+02
LU	Pt	6.69E+02	2.00E+05	2.03E+04

Fig. 2. Environmental impact of producing 1 t of by-products in different categories of indicators.

Meanwhile, WS and CG have considerably lower water demands (13.8 and 9.1 m^3, respectively). Conversely, LU is particularly high for CG (199,939 Pt as it requires large

areas of land due to low productivity per hectare and a waiting time of almost a decade for each harvest. For GOS (20,254 Pt) and WS (668.7 Pt), the values are significantly lower, as they produce annually, optimising LU per tonne produced.

The results presented demonstrate that the three agro-industrial by-products exhibit substantially different environmental performance due to the distinct agricultural, forestry and industrial processes from which they originate. Therefore, it is misleading to assume that they have a low environmental impact simply because they originate from organic systems. Although they are by-products of other processes, they can transfer significant environmental impacts to the materials into which they are incorporated. Likewise, treating different agro-industrial by-products as environmentally equivalent can lead to misguided material choices and incomplete circularity assessments. Processing intensity, determined by agricultural practices and regional supply chains–which vary considerably depending on the product–is a key determinant of environmental performance. Here, the results are strongly influenced by Mediterranean production conditions, including irrigation intensity, fertiliser use and the regional energy mix, which further underscores the importance of geographically contextualised LCAs. Lastly, is important to emphasise the need to analyse indicators other than GWP, as they can highlight local constraints. From a construction material selection perspective, WS may be preferable in applications prioritising low fossil energy demand, while CG may be advantageous where carbon sequestration is prioritised and land occupation is less critical. GOS may require careful consideration in water-scarce regions due to its high irrigation-related impacts.

4 Conclusions

In this study, the environmental impact of three agro-industrial by-products widely available in Portugal and in the Mediterranean region was analysed. These are wheat straw (WS), cork granules (CG), and ground olive stones (GOS). Suitable for use as additives in bio-based construction materials, they can serve different purposes: fibres for reinforcement, granules as lightweight aggregates, among others.

The results demonstrate that the environmental performance of agro-industrial by-products is far from uniform. WS and CG exhibit net carbon dioxide sequestration but carry high eutrophication and land-use burdens, while GOS present positive carbon emissions and significant fossil energy use. These distinctions remind us that the environmental performance of residues reflects the underlying production systems. Despite their biological origin, these materials are not zero-impact, particularly when indicators other than global warming potential and fossil resource consumption are examined. Adopting a circular bioeconomy perspective, this study argues that responsible valorisation of agricultural by-products requires a critical assessment of trade-offs across many impact categories, rather than relying solely on carbon-centric narratives. In doing so, it contributes to the design of more realistic and informed pathways for integrating bio-based residues into sustainable building materials and aligns with broader goals of reshaping the built environment towards circularity, resilience, and ecological performance.

4.1 Limitations

Results were analysed comparatively to identify the materials and categories with the greatest environmental challenges. Due to the lack of benchmarks, impacts could not be quantified in absolute terms. Future research should expand the analysis to full life-cycle impacts, include sensitivity analyses on allocation choices, and assess how regional energy transitions may affect energy-intensive residues such as GOS. Our findings also show that allocation choices can strongly influence the environmental profile of agricultural by-products, particularly when residues have economic value or energy recovery potential.

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Bridging Southern Traditions and Northern Standards: A Multi-Criteria Sustainability Assessment of Earth-Based Solutions

Marwa Dabaieh[1], Jorge Fernandes[2(✉)], and Ricardo Mateus[2]

[1] Department of Urban Studies, Institute of Urban Research, Malmö University, Malmö, Sweden

[2] ISISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal
jorge.fernandes@civil.uminho.pt

Abstract. The construction industry is a major contributor to global resource use and carbon emissions, making low-carbon alternatives essential to achieving climate neutrality. The European Performance of Buildings Directive (EPBD) requirements for whole-life carbon accounting are accelerating the adoption of materials with low embodied carbon. However, local factors such as climate and national regulations pose challenges to the expected functional performance of solutions, potentially altering their overall sustainability performance and how they are perceived. This study examines the feasibility of adopting earth-based construction techniques to support the building sector's low-carbon and green transition in contrasting contexts: Portugal's Mediterranean climate and Sweden's Nordic climate. Earthen solutions are assessed against conventional alternatives in both countries to ensure compliance with national performance requirements. The comparison applies the Methodology for Relative Assessment of the Sustainability of Construction Solutions (MARS-SC), a multicriteria decision-making tool that evaluates sustainability across three dimensions: environmental, functional, and economic. Environmental performance is informed by LCA, which uses both generic and specific data to compare impacts between earth-based and conventional construction systems. Results show that earth-based construction, particularly in Portugal, can provide substantial environmental advantages, achieving up to 50% lower Global Warming Potential than conventional solutions. In Sweden, however, higher labour costs, longer construction and drying times, and the need for additional thermal insulation layers tend to increase costs and can reduce overall sustainability performance despite potential environmental benefits. The paper discusses the key advantages and limitations of earthen materials in each country and highlights conditions under which earth-based techniques can become a robust low-carbon alternative.

Keywords: Earth Construction Techniques · Multi-Criteria Decision Making · Low-Carbon Construction · Environmental Performance

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1 Introduction

1.1 Framework

The construction sector is one of the largest contributors to global greenhouse gas (GHG) emissions and resource consumption. Buildings account for approximately 37% of global energy-related CO_2 emissions when both operational and embodied emissions are considered [1]. As operational energy demand decreases due to improved efficiency standards, embodied carbon accounts for an increasing share of total life-cycle emissions [2]. The European Union policy framework has accelerated this shift toward whole-life carbon accounting, requiring member states to integrate it into building regulations and Energy Performance Certificates [3].

In this context, a recent European Commission report emphasises that while operational emissions have historically received greater focus, addressing embodied emissions is crucial to achieving whole-life carbon neutrality [4]. The document proposes strategies such as using low-carbon bio-based materials, increasing circularity, and building reuse, noting that in some countries, embodied emissions are more relevant because operational emissions are lower. For example, in Portugal and Denmark, operational emissions are only slightly over half of total emissions, and in Sweden, they are even lower. Thus, the potential to cut emissions via operational measures is limited, making other strategies more important in these countries, such as higher use intensity, greater circularity, better use of existing buildings, and low-carbon materials. In the EU building stock, about 25% of life-cycle emissions are upfront embodied emissions from materials in new construction [4], and studies show they can reach 30–60% in highly energy-efficient buildings [5].

Therefore, to achieve climate neutrality, emissions from construction materials must be reduced. In this context, earthen construction is increasingly recognised as an ecological option that diversifies material choices. The aim of this paper is to compare the relative sustainability performance (environmental, functional and economic) of earthen techniques and conventional solutions in different contexts.

1.2 Earth Construction in Northern and Southern Europe

In Mediterranean climates, earthen materials provide performance benefits through their high thermal mass, which regulates indoor temperature fluctuations. Their high heat capacity and thermal inertia moderate indoor temperatures during large diurnal variations [6, 7]. This thermal mass reduces peak heating and cooling demand by absorbing heat during the day and releasing it at night [6]. Since heating needs are lower than in Nordic regions, earthen wall systems can often meet thermal requirements with less supplementary insulation, improving both environmental and economic feasibility.

In Nordic climates such as Sweden's, stricter thermal resistance and moisture safety requirements pose additional challenges. Because earthen materials have low insulation performance, they need extra layers to meet regulatory U-value thresholds [6, 8]. Moisture behaviour is also critical; hygrothermal analysis is required to avoid condensation, frost risk, and moisture accumulation in walls, which exhibit complex heat–moisture interactions [9]. Cold, humid conditions can prolong drying, extending construction

schedules and increasing labour costs. Thus, while environmental benefits may remain, overall sustainability in Nordic climates relies on well-designed hybrid systems that combine earthen materials with sufficient insulation and moisture control. In Mediterranean regions, earthen architecture is rooted in vernacular heritage, which can support social acceptance. In Nordic contexts, limited familiarity and regulatory conservatism may shape stakeholder perceptions despite documented environmental benefits. Earthen construction is also more labour-intensive than industrialised systems [10, 11], and in high-labour-cost settings such as Sweden, this can reduce its competitiveness relative to prefabricated timber or reinforced concrete.

1.3 Sustainability Assessment Needs Multicriteria Tools

Sustainability assessment frameworks stress that environmental gains must be weighed against economic and functional criteria. A material with lower embodied carbon may not be more sustainable if higher labour, time, or compliance costs offset its benefits. Because sustainability is multidimensional, multicriteria decision-making (MCDM) tools are valuable in construction research and practice. Integrated assessment models are needed to evaluate environmental, functional, and economic dimensions simultaneously. Life-cycle assessment provides environmental indicators, while cost analysis and performance compliance cover economic and functional aspects. This integrated approach underpins the MARS-SC method (described in later sections), which compares construction solutions under context-specific conditions. Moreover, technological transitions in construction depend not only on measurable performance but also on cultural and institutional acceptance.

2 Methodology

This paper presents a comparative analysis of conventional and earthen construction materials, using the Methodology for Relative Assessment of the Sustainability of Construction Solutions (MARS-SC), a multicriteria tool developed by Mateus & Bragança [12]. The MARS-SC methodology evaluates sustainability across three dimensions: environmental, functional, and economic. By assessing performance across each dimension, the tool identifies the most sustainable options tailored to specific project requirements, enabling the selection of construction solutions that strike an optimal balance among reduced environmental impact, enhanced functional performance, and economic feasibility. The MARS-SC scoring system normalises the indicators and aggregates them into a composite sustainability score ranging from 0 to 1, where higher values represent better performance.

The evaluation in this study relies on data from LCA studies [13, 14], environmental product declarations (EPDs), and construction cost databases [14, 15]. The conventional solutions were defined as the most common in each country. Earth-based solutions were defined as one of the traditional common in the Portuguese and Swedish contexts.

The maximum U-value for each country was defined in accordance with the legislation in force. In the case of Portugal, it was considered the max U-value allowed for the

most demanding winter season (0.35 W/(m^2.K)). The construction solutions assessed in the study are summarised in Table 1.

Table 1. Construction solutions defined for each country (PT – Portugal; SE – Sweden) [13–15].

Construction System	GWP kg CO_2 eq./m^2	U-value W/(m^2.K)	Cost €/m^2
PT-Ceramic Brick + ETICS	47.6	0.32	119
PT-Brick Cavity Wall Insulated	108.2	0.31	104
PT-Rammed earth wall	31.4	1.29	210
PT-CEB cavity wall insulated	36.5	0.34	286
SE-Typical Reinforced Concrete Wall	325	0.18	214
SE-Typical Fired Brick Wall	275	0.22	252
SE-Rammed earth + straw wall	6.8	0.17	2257
SE-Adobe + straw wall	−15	0.15	1615

3 Sustainability Performance Comparison

3.1 Multi-Criteria Assessment of Construction Solutions

In this study, the MARS-SC was applied to compare four construction systems in each country: two conventional and two earth-based. The environmental performance considered the GWP only, the U-value on the functional performance, and the construction cost on the economic performance. Since the solutions were tailored to comply with the energy performance requirements in each country, the functional performance of all systems is very similar in each country. The differences observed in the results reflect primarily the environmental impact of the materials and the construction costs associated with them. Table 2 summarises the performance scores obtained for the assessed construction systems, and Fig. 1 illustrates the comparative scores of the assessed building systems across the analysed countries.

Across all cases, the earth-based construction system achieved the highest environmental performance, mainly due to low carbon emissions from locally sourced materials and minimal processing. In contrast, conventional systems that rely on cement and fired materials exhibited higher emissions due to energy-intensive production. However, conventional solutions performed significantly better economically, as earth-based systems are more costly due to labour intensity, longer construction times, and limited industrialisation. This cost gap is especially pronounced in Sweden, where construction costs per square meter are considerably higher than in Portugal.

Table 2. Performance scores of the assessed construction systems (EP-Environmental Performance; FP-Functional Performance; EC-Economic Performance)

Construction System	EP	FP	EC
PT-Ceramic Brick + ETICS	0.79	0.99	0.92
PT-Brick Cavity Wall Insulated	**0.00**	**1.00**	**1.00**
PT-Rammed earth wall	**1.00**	**0.00**	0.42
PT-CEB cavity wall insulated	0.93	0.98	**0.00**
SE-Typical Reinforced Concrete Wall	**0.00**	0.64	**1.00**
SE-Typical Fired Brick Wall	0.15	**0.00**	0.98
SE-Rammed earth + straw wall	0.94	0.71	**0.00**
SE-Adobe + straw wall	**1.00**	**1.00**	0.31

In terms of functional performance, most systems showed similar results, as U-values were designed to meet regulatory requirements, with minor differences due to insulation thickness. In Portugal, the lower performance of rammed earth is not fully representative, as regulations allow uninsulated walls under certain conditions, recognising benefits such as thermal and moisture inertia, which can also improve environmental performance by reducing the number of material layers. The overall assessment depends on the weighting of environmental, economic, and functional criteria. Prioritising environmental performance is essential for decarbonisation, though higher costs of low-carbon solutions may require policy support, such as incentives. While earth-based systems are not suitable for all contexts, they are a viable option in many scenarios and help diversify low-carbon construction strategies. Differences between countries were observed (Fig. 1): conventional systems had lower impacts in Portugal than in Sweden, whereas for earth-based systems, the use of straw insulation, due to its biogenic carbon storage, resulted in lower emissions in Sweden than in Portugal.

3.2 Integrated Assessment of Construction Systems and Sustainability Implications

The results demonstrate a consistent hierarchy in environmental performance across all case studies. The earth-based construction systems achieved the highest sustainability scores, primarily due to their low embodied energy and reduced dependence on non-renewable resources. This was followed by the improved conventional system, which outperformed the standard conventional system due to enhanced material efficiency and lower manufacturing energy requirements. Despite these improvements, both conventional systems exhibited significantly higher environmental impacts compared to the earth-based alternative. This ranking remained stable across both countries, confirming the robustness of the findings. Minor variations in performance were observed, mainly influenced by differences in material sourcing, transportation distances, and national production technologies. In contexts where earthen materials were locally available showed greater environmental benefits, as reduced transportation further lowered emissions and energy use.

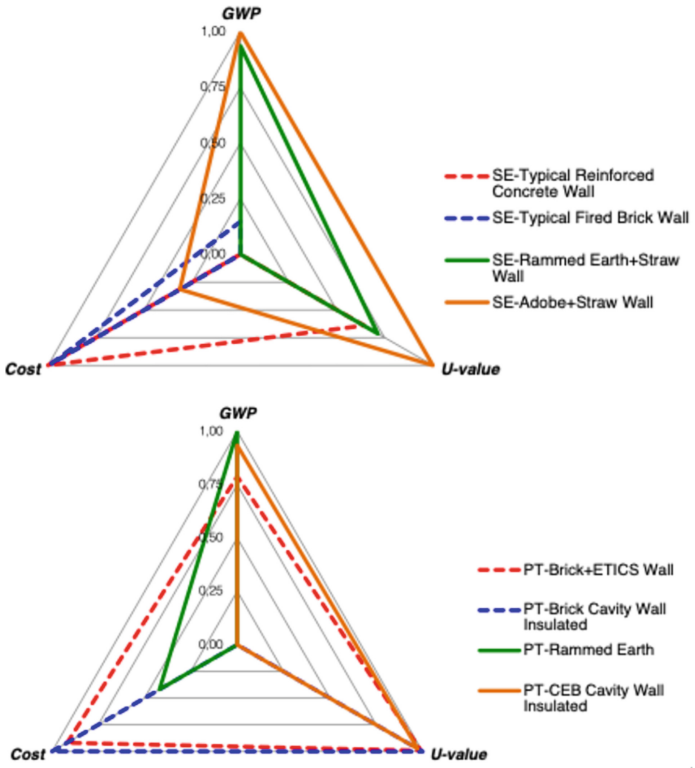


Fig. 1. Comparative environmental performance of construction systems using the MARS-SC method (up: Swedish Context; down: Portuguese context).

The analysis highlights the critical role of material selection in shaping environmental performance. Conventional materials such as cement, steel, and fired clay products were the main contributors to increased embodied energy and carbon emissions. These findings point to clear sustainability gaps in conventional construction, suggesting that improvements in material production or the adoption of lower-impact alternatives could substantially reduce environmental burdens. While earth-based systems demonstrated clear environmental advantages, some challenges remain regarding their broader implementation. These include issues related to standardisation, regulatory acceptance, and integration with contemporary building systems. Addressing these barriers is essential to fully realise their potential in modern construction.

Overall, the results confirm that earth-based construction systems offer a viable low-impact alternative with significant potential to reduce the environmental footprint of the building sector. The application of the MARS-SC methodology proved effective in comparing construction systems and identifying key areas for improvement, particularly in material use and production processes.

4 Discussion

The findings highlight important limitations in assessing the sustainability of construction systems. Although earth-based solutions show strong environmental performance, this outcome is influenced by reliance on a single indicator, which may not fully capture broader environmental impacts. As such, the results should be understood as partial rather than comprehensive. A key insight is the clear tension between environmental and economic performance. Earth-based systems remain significantly more costly, particularly in high-wage contexts, due to labour-intensive processes, limited industrialisation, and longer construction times. This economic constraint represents a major barrier to their wider adoption. The analysis also underscores the strong context dependency of sustainability outcomes. Variations in regulatory frameworks, climatic conditions, and market structures significantly influence performance. In more favourable contexts, earth-based construction becomes more feasible, whereas in stricter or high-cost environments, its limitations are amplified. This indicates that such systems cannot be directly transferred across regions without adaptation. In addition, current assessment methods provide limited insight into the full functional potential of alternative materials. By focusing on standardised performance metrics, important characteristics such as thermal inertia and moisture regulation remain underrepresented, potentially biasing evaluations towards conventional systems.

5 Conclusions

This study highlights that the sustainability of construction systems cannot be determined solely by environmental performance, as assessment methods and selected indicators significantly influence outcomes. It emphasises the importance of adopting a more comprehensive evaluation framework that captures environmental, economic, and functional dimensions. The findings indicate that alternative construction approaches, such as earth-based systems, require supportive regulatory conditions, greater efficiency, and more inclusive assessment methods to be evaluated fairly and implemented effectively. Ultimately, their role in sustainable construction depends on context-sensitive strategies rather than universal application.

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Environmental Footprint Index for Industrialized Construction

Angelos Dampalis and Yiannis Xenidis(✉)

Aristotle University of Thessaloniki, Thessaloniki 54124, Greece
ioxen@civil.auth.gr

Abstract. The construction industry is challenged to address the longstanding problem of low productivity while simultaneously reducing carbon dioxide emissions, as it remains one of the largest emitters worldwide. This paper examines industrialization and climate neutrality as key pathways for tackling these dual demands. A literature review is conducted to identify existing approaches for quantifying both industrialization and carbon footprint. The calculation methods identified are compared and analyzed to provide the foundation for developing a new index that measures these two dimensions simultaneously in industrialized building projects. The research focuses on Stage A (product and construction process) of the construction lifecycle and particularly takes into consideration embodied carbon. The proposed Environmental Footprint Index for Industrialized Construction (EFIC) integrates productivity indicators and prefabrication - two primary measures of industrialization - while using life cycle assessment to evaluate carbon footprint. The study then determines the relation of these factors and establishes a normalization procedure to finalize the index's mathematical formulation. To validate the index, a case study is carried out on four industrialized buildings that employ different industrialization techniques. Three out of four buildings are drawn from analyses of previous research works while the fourth is a case of a real building under construction. The resulting scores and rankings indicate that the 3D-printed building performs best overall, achieving the highest level of industrialization while also demonstrating the lowest environmental impact. The limitations and directions for further elaboration of the validated index are discussed for future research.

Keywords: Construction Industrialization · Construction Productivity · Construction Carbon Footprint · Life Cycle Assessment · Environmental Footprint Index for Industrialized Construction

1 Introduction

Construction industry is considered as one of the most important sectors of the economy, generating annual revenues of approximately three trillion dollars, which corresponds to 6% of global Gross Domestic Product (GDP) (De Soto et al., 2018). Global population is estimated to reach 9.7 billion by 2050 thus increasing the demand for new infrastructure and buildings up to 415 billion square meters of total usable floor space (López-Guerrero,

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Vera, & Carpio, 2022). This increase combined with urbanization forces the construction industry to scale up and implement construction methods, including industrialized solutions, technological innovations and effective management practices on project level that will enhance productivity and efficiency (Stehn & Jimenez, 2023).

At the same time, buildings are among the biggest polluters, producing some 34% of global greenhouse gas emissions (United Nations, 2025); therefore, a significant reduction of CO_2 emissions becomes imperative.

The potential of utilizing methods of industrialized construction towards fulfilling both goals, i.e., increased productivity and climate neutrality is recognized and even attempted through specific strategies and policies at global and regional levels (Yao et al., 2022). Yet, currently, no assessment methods or tools exist to provide quantified evidence of the success of such attempts at the component level, i.e., the building. The rest of this paper discusses the background and proposes such an index for assessing with a single value the degree of industrialization and climate neutrality of buildings.

2 Background

2.1 Industrialization of Construction

The adoption of new technologies and innovative solutions in the construction industry is at a low pace, mainly due to inherent features (e.g., great number of stakeholders, complex supply chains) of the industry that cause high risks (Van Der Heijden, 2023). The impact of these features on productivity could be mitigated by implementing Industrialized Construction and/or Construction 4.0 methods. Industrialized construction (IC) incorporates industrial principles, innovative processes, and smart technologies in design, factory production, transportation of structural elements, and assembly of structures (Wuni, Wu, & Shen, 2021). Construction 4.0 is defined as the digitization and automation of the industry that enables real-time, horizontal, and vertical integration and connectivity of stakeholders throughout the entire construction project lifecycle, promoting the advancement of construction processes by bridging the gap between the physical and cyber environments (El Jazzar et al., 2021).

The benefits originating from Construction 4.0 include reduced costs throughout the life cycle, increased productivity, improved construction quality, and reduced waste of building materials (Ismail et al., 2022). In addition, the number of workplace accidents is reduced and there is a noticeable decrease in energy consumption, air and soil pollution, noise, dust, and water consumption (López-Guerrero, Vera, & Carpio, 2022). Thus, there is a strong connection between industrialization of construction and the climate crisis that the world is facing.

2.2 Climate Neutrality

Climate neutrality is defined as a state of zero carbon emissions which can be achieved by balancing the total amount of carbon emissions over a certain period via carbon offset or removal initiatives (Chen et al., 2023). Climate neutrality and buildings are connected through embodied and operational carbon. Embodied carbon includes carbon dioxide

emissions related to the entire life cycle of the building, excluding its operation, a part which is called operational carbon (Fang et al., 2023). Embedded carbon emissions originate from building materials, the construction process, the transport of materials and waste, maintenance, repair and end-of-life activities (Greer & Horvath, 2023). The total carbon emissions associated with a building are typically attributed to embodied carbon (around 20%) and operational carbon (around 80%) (Fang et al., 2023).

In order to reduce carbon emissions, various strategies have been proposed focusing on different stages of a building's life cycle. These strategies include usage of low-carbon materials in construction, waste management during the whole life cycle and construction of nearly zero energy buildings (nZEB). Also, nZEB can be industrialized products constructed using Construction 4.0 technologies that promise even lower carbon emissions. The promotion of such an approach requires evidence on the efficiency of these buildings and such evidence is provided by relevant assessment methods.

2.3 Assessment Methods

Assessing industrialization of construction and climate neutrality of buildings is an essential, yet difficult to apply process (Stehn & Jimenez, 2023). The assessment of industrialization parameters is based on productivity indices, the prefabrication rate, technology valuation metrics, and economic valuation metrics:

- Productivity indicators are very commonly used in construction aiming at calculating the productivity of an activity or an entire project using numerical formulas, which usually assess the ratio of an output's size to the time required for its delivery (Lowe, 1987).
- The prefabrication rate refers to the percentage of construction elements that have been prefabricated off-site and contributes to measuring the degree of industrialization of a construction project (López-Guerrero et al., 2022).
- Technology valuation metrics measure the integration and application of new technologies and industrialization practices in construction (De Soto et al., 2018).
- Economic valuation metrics quantify the comparison between conventional and industrialized construction methods, in terms of cost and resource efficiency (De Soto et al., 2018).

The most widely used approach for environmental assessment of buildings is Life Cycle Assessment (LCA), which allows the assessment of CO_2 emissions and energy used in the various stages of construction (Aghasizadeh et al., 2022). Another way to environmentally assess buildings is green certificates, which verify a building's reduced energy consumption and carbon footprint and relate to its good thermal capacity and the sustainability of its construction (Allouhi et al., 2015). Lastly, embedded emissions and operational emissions are calculated using numerical models for the number of materials used in construction and for the operational energy consumption required (Hong et al., 2014).

3 Methodology

A new index called Environmental Footprint Index for Industrialized Construction (EFIC) is proposed to assess both the degree of industrialization and the climate neutrality of buildings by integrating approaches from existing assessment methods. The index comprises three factors, namely productivity, industrialization and carbon footprint. The first two are calculated with the use of Eqs. (1) and (2):

$$P = \frac{Building\ Area\ \left(m^2\right)}{Construction\ duration\ (hr)} \tag{1}$$

$$IR = \frac{100\%^*\ Volume\ or\ Mass\ of\ Industrialized\ elements\ \left(m^3\ or\ kg\right)}{Total\ Volume\ or\ Mass\ of\ building\ materials\ \left(m^3\ or\ kg\right)} \tag{2}$$

The Industrialization Rate of Construction is a variation of prefab rate, which renders it applicable to all types of industrialized buildings.

The building's carbon footprint is assessed through LCA with the use of appropriate software tools and reference to carbon emissions per square meter.

The three factors addressed in the proposed index are not interdependent; in fact, they are strongly related, yet the nature and, moreover, the quantification of these relations is very hard to explicitly determine. Therefore, the following general assumptions are made in the context of this study:

- Increased productivity leads to increased industrialization rate.
- Increased productivity leads to decreased carbon footprint.
- Increased industrialization rate leads to decreased carbon footprint.

While debatable, particularly when considering the construction methods and specific features of individual cases, these assumptions enable the determination of the boundary conditions required for a proof of concept of the proposed index: (a) increased productivity, high industrialization rate, and reduced carbon footprint result to an increased index value, which indicates an industrialized construction that achieves climate neutrality. On the other hand, low productivity, low industrialization rate and increased carbon footprint result in a reduced index value, which indicates a construction, which is not highly industrialized and/or environmentally friendly.

The incorporation of factors featuring different measures, units, and scales into a single index requires first data normalization. In the context of this research the Min-Max normalization method is selected for application as it is commonly used for the development of indices (Jahan & Edwards, 2014). The mathematical representation of the EFIC index is then formulated using the following normalized variables:

- $\boldsymbol{P}_{\text{norm}}$: Normalized productivity in the interval [0,1] (0: minimum value, 1: optimal value).
- $\boldsymbol{IR}_{\text{norm}}$: Normalized industrialization rate in the interval [0,1] (0: minimum impact of industrialization on the building, 1: fully industrialized building).
- $\boldsymbol{E_{CO2}}_{\text{norm}}$: Normalized carbon footprint in the interval [0,1] (0: minimum value, 1: optimal value (climate neutral building)).

Since all variables are assumed to be of equal importance and equally contributing to the final result, the Euclidean distance is used for the calculation of the index. The index values range from 0 to 100, a scale commonly adopted in similar indexes to enhance interpretability and facilitate comparison. Accordingly, the mathematical formulation of the EFIC index is given by Eq. (3).

$$EFIC = \frac{100^{*}\sqrt{((1 - Pnorm)2 + (1 - IRnorm)2 + (1 - ECO_2\text{norm})2)}}{\sqrt{3}} \quad (3)$$

The implementation of the proposed index is tested in four industrialized building projects, and its application and respective results are presented in Sect. 4.

4 Case Study

Life Cycle Assessments (LCA) were conducted with the use of the One Click LCA software tool for four buildings, based on: (a) the building area (set to a maximum of 500 m^2 to allow comparison and overcome a tendency of smaller construction projects to exhibit higher carbon emissions per square meter (Tavares, Lacerda, & Freire, 2018)), (b) the assumed lifecycle (set to 50 years and limited to stage A (A1-A5) of the Life Cycle according to EN 15978:2011 standards (Huang et al., 2022), while focusing on materials and the construction process, i.e., only to embodied carbon emissions), (c) the building location (set to the city of Thessaloniki as a common geographical context for the analysis), (d) the transportation distance of materials (set – based on real data – to 40 km for local suppliers, 200 km for the prefabrication plant, and 1,000 for the transport of the 3D printer), (e) the functional unit (expressed in m^2, and the result expressed in $kgCO_2e/m^2$), and (f) the life cycle inventory for each case. The four industrialized buildings considered in this study are briefly presented in Table 1, while Table 2 shows the summarized life cycle inventory of all buildings.

The data presented in Table 2 are then used for assessing the three factors addressed in EFIC. Table 3 presents the results for each factor both before and after normalization. The table's last column presents the EFIC value for each building.

As shown in Table 3, Building 3 presents the highest index value. This is consistent with the expectations, as the high level of industrialization, increased productivity, and low carbon footprint of Building 3 lead to significantly higher performance according to the proposed index. The comparison indicates that additive construction provides the most effective combination of industrialization and climate neutrality. The lightweight structural systems used in Buildings 1 and 2, also, show satisfactory performance and may represent a suitable solution for small-scale constructions due to their overall satisfactory profile.

Table 1. The selected buildings for the case study.

Building	Structural System	Total floor area (m^2)	Total duration of construction (hr)	Source of case study
1	Prefabricated building with a light steel frame (LSF)	136	2784	Tavares et al. (2021)
2	Prefabricated building with a timber frame (WF)	136	2784	Tavares et al. (2021)
3	3D-printed house	90	1008	Abdalla et al. (2021)
4	Prefabricated concrete building (walls and slabs)	500	3360	this research

Table 2. Life Cycle Inventory for each building.

Materials for buildings 1,2 (kg)	Building 1 (LSF)	Building 2 (WF)	Building 3 (3D-printed)	Building 4 (prefab_C)	Materials for buildings 3,4 (kg)
Concrete	12480	12480	12480	1130400	Concrete
Reinforcing steel	385	385	385	24600	Reinforcing steel
Formwork wood	244	244	244	–	Formwork wood
Polyethylene	9	9	9	110	Polyethylene
Cold-formed Steel	9551	–	3000	7350	Mineral wool
Structural wood	–	5953	16200	–	Micro silica
Oriented strand board	6942	6942	900	–	Superplasticizer
Aluminium	–	145	38700	–	Cement
Gypsum board	7744	7744	9	–	Viscosity modifying admixture
Ceramic tiles	4000	4000	58050	–	Fine Aggregate

(*continued*)

Table 2. (*continued*)

Materials for buildings 1,2 (kg)	Building 1 (LSF)	Building 2 (WF)	Building 3 (3D-printed)	Building 4 (prefab_C)	Materials for buildings 3,4 (kg)
Polyester	59	59	15300	–	Fly ash
Polyethylene foam	59	59	–	328000	Concrete C30/37
Mineral wool	3510	3510	–	4290	Insulating Plaster
Granite	4900	4900	–	16360	Structural wood
Wooden slaters	1350	1350	–	11470	Oriented strand board
Steel connectors	–	234		14705	Ceramic tiles
				110	Polyester
Energy and Water Consumption					
Energy (KWh)	3240	3240	1890	11800	Energy (KWh)
Water (m^3)	0.215	0.215	16200	103000	Water (m^3)

Table 3. Factors' values before and after normalization and EFIC value for each building.

Building	P		IR		E_{CO2}		EFIC
	Normalization						
	Before	After	Before	After	Before	After	
1	0.049	0.091	18.64	0.067	387	0.587	21.10
2	0.039	0	13.59	0	177	1	18.35
3	0.089	0.455	88.9	1	530	0.305	49.00
4	0.149	1	22.98	0.125	685	0	23.30

5 Conclusions and Recommendations

This study proposes an Environmental Footprint Index for Industrialized Construction (EFIC) to simultaneously assess buildings' performance against industrialization and climate neutrality. The application of the proposed index in a case study reaffirmed that building materials are the main contributors to carbon emissions, while lighter structural systems demonstrate improved environmental performance. Also, it highlighted 3D printing as a very efficient construction method compared to traditional ones in the context of industrialization and climate neutrality. EFIC is a first step that with further improvements (e.g., LCA across the entire life cycle) could provide a useful tool for evaluating construction methods against environmental and productivity requirements.

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Proposing a Dynamic Carbon Payback Time Approach for the Assessment of Green Roofs

Kleoni Ntouvli(✉) and Katerina Tsikaloudaki

School of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
kntouvl@civil.auth.gr

Abstract. This study presents a dynamic carbon payback time (CPBT) approach, suitable for the dynamic life cycle analysis (DLCA) of green roofs (GRs). Previous studies focused on calculating CPBT according to the static LCA approach. The findings reveal that the extensive type achieved CPBT between 14 to 42 years. The semi-intensive type and the intensive type offset between 27–32 and 32–36 years, respectively. However, a DLCA approach improves the accuracy of LCA by addressing the inconsistencies of temporal assessment. By incorporating temporal factors, a more comprehensive understanding of how green roofs contribute to carbon offset over time is achieved. To assess the effects of unequal annual carbon emission flow, a dynamic CPBT (DCPBT) is proposed, considering a year-by-year carbon emissions examination analysis is considered. The analysis includes the annual carbon sequestration, the annual carbon savings, and the annual embodied carbon emissions. The DLCA involves five stages: production, transportation, construction, operation/maintenance, and end-of-life stages. This approach allows for a more accurate understanding of the long-term benefits of GRs in mitigating climate change.

Keywords: Carbon · Green Roof · Dynamic Carbon Payback Time · DLCA

1 Introduction

Climate change is considered one of the main challenges humanity is facing in the 21st century [1]. As the built environment contributes significantly to greenhouse gas emissions [2], the implementation of mitigation and adaptation strategies against climate change is required. Green roofs (GRs) are promoted as an effective green infrastructure strategy for reducing carbon emissions.

Based on the substrate thickness, two major types of GRs can be distinguished in the literature, i.e., extensive and intensive GR types. Another type is also considered in literature, known as semi-intensive [3]. A GR consists of several components, above the normal layers of a flat roof, including, from bottom to top: a waterproofing membrane, a root barrier, a protection layer, a water storage, and drainage layer, a filter layer, substrate (growing medium or soil), and vegetation [4, 5].

The emissions associated with the GR system are classified as both direct and indirect impacts [6]. The direct impact is related to the photosynthesis process. Through this

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mechanism, GR systems capture and store carbon in plant biomass and the soil medium. The indirect impact concerns emission reductions resulting from energy savings. The processes of evapotranspiration and shading contribute to a reduction in indoor air temperature, thereby lowering a building's energy consumption for cooling, and thus leading to decreased CO_2 emissions [6]. However, the integration of a GR system is followed by the associated environmental impacts, which are identified as "embodied carbon." The additional structural requirements of GRs might increase the quantity of material required, thereby raising embodied carbon. As a result, the environmental impact of the upstream processes may outweigh the carbon savings from GRs.

The aim of the study is to propose a novel approach for calculating Carbon Payback Time using a Dynamic Life Cycle Assessment. To address the identified gaps, this study seeks to answer the following key questions:

Q1.	"What are the key methodological distinctions between conventional Life Cycle Assessment (LCA) and Dynamic Life Cycle Assessment (DLCA)?"
Q2.	"How many years are required for a GR system to offset its carbon emissions?"
Q3.	"In what manner can the Dynamic Carbon Payback Time (DCPBT) concept be implemented for evaluating a GR system?"

Firstly, the study presents the methodological differences of static and dynamic LCA, focusing on how the variables of DLCA are introduced into a GR system. Then it briefly outlines the methodology used to identify relevant papers in the existing literature on the CPBT concept, as applied to GR case studies and presents the main findings. Finally, a new approach for calculating DCPBT is proposed.

2 Background: LCA vs DLCA

Life cycle assessment is widely used to quantify the environmental performance of a product, process, and system throughout its life cycle. However, static LCA does not consider potential temporal or spatial variations over the assessment lifetime. The methodological differences between conventional and dynamic LCA are widely established in the literature, particularly regarding temporal differentiation of emissions, time-dependent inventory flows, and variables considered. Table 1 summarizes the main methodological differences between conventional LCA and DLCA.

DLCA considers when emissions are generated and how they evolve over time. This is particularly important for GRs, as their environmental benefits appear gradually and change over time. Dynamic variables related to buildings have been widely discussed in the literature [9, 13], however, dynamic variables specifically associated with GRs remain unexplored.

Table 2 highlights that several variables are relevant for both systems. However, variables such as energy evolution, technological advances, and device degradation are commonly addressed at the building scale. Carbon sequestration is mainly related to the GR system, while in the case of building, sequestration mechanisms are related to bio-based construction materials, known as biogenic carbon [14].

Table 1. Methodological differences between conventional LCA and DLCA

Criterion	Conventional LCA	Dynamic LCA	References
Temporal variation	Static emissions throughout the lifecycle	Time-dependent; emissions are generated at specific time-step	[7, 8]
Treatment of emissions	Assumes the same reference time for all emissions.	Considering the effect of the timing of the emissions	[9]
Life Cycle Inventory	All emissions for a given pollutant are added into a single aggregate	Each emission is a function of time	[10, 11]
Characterization factors	Constant over time	Dynamic; account for the atmospheric residence time of each GHG emission.	[11]
Weighting factors	Static values;	Time-dependent; influenced by economy and society	[10, 12]
Variables	Usually ignored	Technical, cultural, social, and environmental;	[9]
Spatial differentiation	Static	Considering spatial variability; local weather data etc.	[9, 12]
Accuracy for long-life systems	Steady-state models decrease the accuracy	Higher accuracy due to temporal differentiation	[9, 11]
Data requirements	Low; Available databases	Higher; Requires temporal datasets	[13]
Computational complexity	Relatively simple modelling	More complex modelling and calculations	[7]

Table 2. Key dynamic variables and parameters affecting DLCA for buildings and GR systems.

Dynamic variables and parameters	Building	GR system
Occupants and behavior	✔	✔
Energy evolution	✔	
Temperature changes	✔	✔

(*continued*)

Table 2. (*continued*)

Dynamic variables and parameters	Building	GR system
Technological advances	✔	
Degradation of materials	✔	✔
Degradation of devices	✔	
Material flows	✔	✔
Waste management	✔	✔
Carbonization	✔	
Carbon sequestration	✔	✔
Dynamic characterization factors (CFs)	✔	✔
Dynamic Weighting factors (WFs)	✔	✔

3 Methodology

Sourcing GR's LCA case studies from the literature and identifying those that incorporate CPBT concept was one of the main goals of our research. Section 3 is part of a broader research study and focuses on presenting the CPBT results identified in the existing literature. The survey was based on Scopus and Web of Science (WoS) databases, applying three groups of search terms to titles, abstracts, and keywords: "green roof AND LCA", "green roof AND carbon payback time", "green roof AND carbon emissions". The analysis focused on peer-reviewed publications relevant to the research topic. It needs to be noted that there is quite limited exploration of the topic in the existing literature. Then, based on the identified gap in existing literature, a new approach for the calculation of DCPBT is developed and presented (Sect. 5).

4 Carbon Payback Time

The number of years required for cumulative cash flows to compensate for the initial investment costs is known as the simple payback time [15]. Even though it ignores cash flows after the payback period, it is a popular tool for appraising investments since it is simple to use and comprehend. Payback times have been created to offer a temporal perspective that reflects on the temporality of impacts. The basic idea is to figure out the period it requires to compensate up for the "cradle-to-gate" impact of any system [7]. The period required a GR system to compensate for its emissions, determining the environmental benefits of this system, which is known as the carbon payback time (CPBT) [16]. The simple CPBT method for GRs is calculated via Eq. (1)

$$\text{Carbon payback time} = \frac{C_e}{C_o} \tag{1}$$

where C_e is the initial embodied GHG emission, and C_o denotes the annual emissions savings and sequestration through operation stage.

Kuronuma et al., [17] developed two sequestration rate scenarios to calculate the CO_2 payback time of extensive modular GRs for different plant species. Their hypothesis in the first scenario was that GR plants would only start to sequester CO_2 in the first year following construction (Eq. 2), whereas in the second scenario, the plants sequester the same amount of CO_2 annually (Eq. 3).

$$CO_2 \text{ payback time} = \frac{CO_{2\,e-p} - CO_{2\,r-s}}{CO_{2\,r-e} - CO_{2\,e-m}} \tag{2}$$

$$CO_2 \text{ payback time} = \frac{CO_{2\,e-p}}{CO_{2\,r-s} - CO_{2\,r-e} - CO_{2\,e-m}} \tag{3}$$

where $CO_{2\,e-p}$ is the amount of CO_2 emitted during the production of the GR system, $CO_{2\,r-s}$ is the annual CO_2 reduction due to CO_2 sequestration, $CO_{2\,r-e}$ is the annual CO_2 reduction due to energy savings and $CO_{2\,e-m}$ is the annual CO_2 emission from maintenance of the GR.

Table 3 summarizes the carbon payback time (CPBT) reported in the literature for different types of GRs. The results indicate considerable variability depending on the roof type, climatic conditions, and system configuration.

Table 3. Carbon payback time of green roof types.

GR type	Lifespan (years)	CPBT (years)	Publication information (reference, country)
Extensive (modular)	45	14.0–15.9	[17], Japan
Extensive (modular)	45	5.8–8.5	[17], Japan
Extensive	45	26	[18], Spain
Extensive	45	42	[18], Italy
Extensive	45	41.5	[19], Italy
Semi-intensive	45	27	[18], Spain
Semi-intensive	45	32	[18], Italy
Semi-intensive	45	32	[19], Italy
Intensive	45	32	[18], Spain
Intensive	45	36	[18], Italy
Intensive	45	36	[19], Italy

Most studies focus on the extensive GR type, while other types are less investigated. Regarding the extensive type, the CPBT period achieved between 14 to 42 years. Semi-intensive type counterbalance between 27–32 years, and intensive type counterbalance between 32–36. The CPBT values show significant variation between different types of GRs. The findings in most studies reveal that extensive GRs have a lower CPBT than semi-intensive and intensive systems, mainly due to the thinner substrate thickness, lower amount of materials, and decreased carbon emissions.

The results of the studies conducted in a Mediterranean climate [18, 19] demonstrate that, depending on climatic factors, the emissions CPBT for different types of GRs is frequently shorter than the expected lifetime (26–42 years). GRs appear to have the potential to offset their initial CO_2 emissions within their lifetime. To ensure that carbon payback periods for extensive GRs are relatively short (5.8 to 15.9 years) it is required to include both CO_2 sequestration by vegetation and energy savings [17] in the calculations. The differences in CPBT values between studies can be attributed to factors such as climatic conditions, the GR's design, geographical location., LCA process and associated methodology (system boundary, stages and components included). Since the conventional LCA depends on static data and is unable to convey dynamic variables, findings may result in notable differences between study outcomes and practical processes [20].

5 Dynamic Carbon Payback Time

Previous Eqs. (1), (2), and (3) are applicable in the case of GRs' static LCA, however, they are inappropriate in the context of the DLCA approach. Yet, the temporal dimension remains unexplored, in terms of CPBT concept. To assess the effects of unequal annual carbon emission flow, a dynamic CPBT (DCPBT) is required, which incorporates inconsistent annual carbon sequestration, annual carbon savings, and maintenance of the GR. The Dynamic Carbon Payback Time (DCPBT) is determined using Payback Period Method with Uneven Cash Flows [22].

$$\text{DCPBT} = (n-1) + \frac{C_o - \sum_{i=1}^{n-1} C_i}{C_n} (\text{years}) \tag{4}$$

where n is the year in which the cumulative cash flow exceeds the initial carbon emission.

The DCPBT is therefore equal to (n−1) plus a fractional part of year n. The first term $(n-1)$ of Eq. (4) represents 1 year less than the number of years the cumulative carbon emission flow takes to exceed the initial embodied carbon EC_o. The second term represents the fractional year required to offset the remaining portion of the initial emissions. C_o equals the initial carbon emissions (kg CO_2) in year 0, associated with production, transportation, and construction. $\sum_i^{n-1} C_i$ is the summation of net carbon flows ($C_1 + .. + C_{n-1}$) from years 1 to $n-1$, expressed in kg CO_2, and C_n is the net carbon flow in year n. Table 4 presents the annual carbon emissions for a hypothetical GR system, with a total service life of T years. The DLCA process includes five stages: production, transportation, construction, operation, maintenance, and end of life stage. Year-by-year records of carbon flows are required to identify the temporal distribution of both emissions and environmental benefits throughout the life cycle of the GR.

It is assumed that production, transportation and construction stages occur in year 0, thus the carbon emissions (C_0) are equal to initial embodied carbon (EC_0). Since the manufacturing stage has been identified as the most impactful [21] based on literature surveys, due to the high energy and raw material requirements during material production, the largest carbon emissions occur in year $t = 0$. Net carbon emissions flows are denoted C_0 to C_{T-1}. For each year $t = 1$ to $T-1$ the net emissions are calculated by subtracting emissions outflows (from maintenance activities) from the emissions inflows

Table 4. Dynamic Carbon payback time method.

Year	EC[a]	C_{SEQ}[a]	C_{SAV}[a]	C_{MAIN}[a]	Math Type	Carbon flows- C_i [CO_2 kg]	LCA Stages[b]
0	EC_0	0	0	0	EC_0	C_0	P + T + C
1	0	C_{SEQ1}	C_{SAV1}	C_{MAIN1}	$C_{SEQ1} + C_{SAV1} - C_{MAIN1}$	C_1	O + M
2	0	C_{SEQ2}	C_{SAV2}	C_{MAIN2}	$C_{SEQ2} + C_{SAV2} - C_{MAIN2}$	C_2	O + M
….	….	….	….	….	….	….	O + M
n−1	0	C_{SEQn-1}	C_{SAVn-1}	$C_{MAINn-1}$	$C_{SEQn-1} + C_{SAVn-1} - C_{MAINn-1}$	C_{n-1}	O + M
n	0	C_{SEQn}	C_{SAVn}	C_{MAINn}	$C_{SEQn} + C_{SAVn} - C_{MAINn}$	C_n	O + M
….	….	….	….	….	….	….	O + M
T−1	0	C_{SEQT-1}	C_{SAVT-1}	CMAINT−1	$C_{SEQT-1} + C_{SAVT-1} - C_{MAINT-1}$	C_{T-1}	O + M
T	EC_T	0	0	0	EC_T	C_T	T+ E

[a] EC = Embodied carbon, C_{SEQ} = Carbon sequestration, $C_{SAV=}$ Carbon savings

[b] P=Production, T = Transportation, O=Operation, C=Construction, Main = Maintenance, E = End-of-life

(carbon savings and sequestration during the operation stage) of the corresponding year. The end-of-life stage occurs in the year *T*. The end-of-life process involves demolition, transportation, and waste management activities.

Figure 1 provides a schematic representation of Eq. (4). The horizontal axis represents time (years), while the vertical axis corresponds to carbon flows. The curve shows the cumulative net carbon emissions flows (blue color). The annual embodied carbon emissions are indicated in red, while the annual carbon savings and sequestration are indicated in green. The cumulative net carbon emissions flow value reaches zero between t = n−1 and t = n, corresponding DCPBT. Then, DCPBT can be determined via linear interpolation. In case the cumulative net carbon emissions never become zero - due to low value annual carbon savings and sequestration relative to the initial embodied emissions - the DCPBT (Eq. 4) is undefined or considered infinite. This situation indicates that the GR system does not achieve carbon offset within its service life.

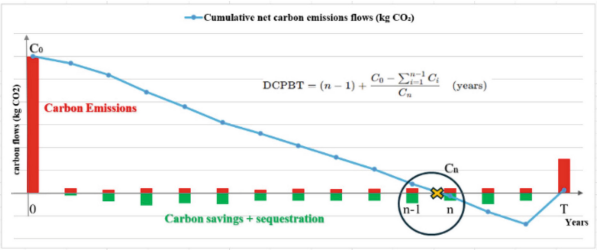


Fig. 1. Dynamic Carbon Payback Time (DCPBT) representation.

6 Conclusion

This study highlights the methodological distinctions between conventional LCA and Dynamic LCA, while summarizing the CPBT reported in the literature for different types of GRs (14–36 years). A novel approach for calculating the DCPBT was proposed, allowing for a more accurate, year-by-year assessment of carbon flows and environmental benefits over the life cycle of GRs. The DCPBT approach, which has been explained, is an important step in investigating the entire environmental performance of GRs, aiding practitioners and researchers in sustainable building design decisions.

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From Stock to Supply: A Regional Screening Approach of Bridge Reuse Potential for Circular Management

Elie Issa[1,2(✉)], Irina Stipanovic[1], and Andreas Hartmann[1]

[1] University of Twente, Drienerlolaan 5, 7522, NB Enschede, Netherlands
Elie.issa@utwente.nl
[2] CEMOSA, Calle Benaque, 929004 Málaga, Spain

Abstract. Infrastructure asset managers are under pressure to reduce embodied impacts and retain material value across assets, yet circular economy ambitions remain difficult to translate into portfolio-scale decision support. In bridge management, component reuse is often identified as a high-value circular strategy because it preserves functional value more effectively than conventional methods, but its implementation is hindered by fragmented information, reverse logistics challenges, operational disruptions, and environmental and regulatory constraints. This paper develops an indicator-based regional screening approach to support the early identification of bridges with promising circular potential. This was derived using a PRISMA-guided scoping review of 52 studies from Scopus and Web of Science and structured into five factors: supply readiness and remaining value; harvesting and reverse logistics feasibility; network disruption pressure and network role; circular ecosystem and match potential; and environmental and regulatory constraints. To complement the review with practice-based judgement, a hybrid expert-weighting survey combining the Analytic Hierarchy Process and budget allocation was conducted with seven experts from Croatia and Slovenia. The results indicate that supply readiness and remaining value received the highest priority, followed by network-related and ecosystem-related considerations. The proposed approach helps bridge the gap between stock-based circular assessments and component-level analysis by showing where further circular investigation is most justified using typical asset management and GIS data.

Keywords: Circular economy · Bridges · Asset management · Regional Screening · Component reuse

1 Introduction

Infrastructure asset managers are increasingly expected to deliver renewal pro-grammes that reduce embodied impacts and retain material value. As highlighted in the UNEP Annual Report 2023, circular economy strategies, which aim to do so through life extension, reuse, and high-quality recovery are gaining traction in infra-structure management [1]. Among circular strategies, component reuse is frequently framed as a high-value pathway because it preserves functional value rather than down-cycling materials, but it remains difficult to scale and prioritize within day-to-day asset management

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because it requires earlier coordination and more evidence than conventional renewal or maintenance decisions [2].

A practical issue is that reuse is possible only when asset owners can anticipate feasible supply and plan early for harvesting, logistics, and compliance before project tenders are finalized. Chen et al. [3] shows that reverse logistics implementation is heavily constrained by operational barriers, such as collection, sorting, storage, and quality control, which are difficult to resolve once project delivery constraints are in place. El Hafiane et al. [4] similarly highlight persistent implementation barriers, including fragmented supply chains, uncertain reverse logistics capacity, and the lack of standards. For bridge assets, circular decisions also require detailed and costly information, including component inventories, structural conditions, connection and dismantling details, verification and testing, and documentation completeness. Cetin et al. [5] illustrate this challenge in the context of material passports, detailing the heavy data requirements and the practical constraints on data availability and validation across stakeholders at various lifecycle stages. As a result, reuse opportunities are often discovered late, after decisions about scope, timing, and traffic management have already narrowed the available option space [6].

At regional scale, circular planning often begins with material stocks and quantities, since these can be estimated across large territories using secondary data. Rajaratnam et al. [7] demonstrates how remote sensing enables scalable stock mining to help identify the locational dynamics of secondary materials. While stock mapping supports recovery and recycling planning, it does not prioritize reuse, because reuse depends on feasibility and value-retention conditions that cannot be inferred from quantity alone [8]. Scalable screening approaches are therefore needed to identify where follow-up reuse testing is most justified and cost-effective, without requiring passport-level detail for every asset in the region [9]. This study addresses the need by developing a screening-stage regional approach for bridge asset managers that translates reuse feasibility requirements into a compact set of indicators computable primarily from standard Asset Management System (AMS) data and GIS layers. This approach enables high-effort, component-level circular analyses to be targeted only where justifiable and ensures that circular options can be evaluated before delivery constraints are fixed.

2 Methodology: Factor Identification and Indicator Derivation

2.1 Literature Search Methodology

Although a growing body of research supports circular assessment in the built environment, its insights remain difficult to translate into a practical regional screening logic for bridge portfolios. Chang et al. [10] show that BIM- and GIS-based approaches can be used to estimate and map material stocks at scale, which is valuable for understanding resource distribution across space. Li et al. [11], however, show that circularity indicators remain highly fragmented and unevenly developed beyond the individual asset level, limiting their usefulness for systematic portfolio-level screening. To identify a more operational factor and indicator structure at the regional scale, a PRISMA-guided scoping review was conducted following the PRISMA 2020 reporting guidance [12]

Scopus and Web of Science using one broad core query and four targeted variants covering portfolio-scale screening, decision-support, transferable built-environment studies, and spatial or GIS-oriented circularity research. Following deduplication and staged screening, 52 studies were retained.

2.2 Hybrid Analytical Hierarchy Process/Budget Allocation Weighting

To complement the literature-derived factor structure with practice-based judgement, a hybrid weighting survey was conducted with seven experts involved in circular infrastructure projects. Experts were selected to reflect roles relevant to early bridge screening, including project and asset management, consultancy, and research. The respondents were based in Croatia and Slovenia, which was considered appropriate because the future empirical application of the approach will use Croatian motorway data. Ten experts were invited, and seven completed responses were obtained.

At the factor level, the Analytic Hierarchy Process (AHP) was used. AHP is a multi-criteria decision-making method in which respondents compare pairs of criteria to express their relative importance [13]. In this study, the five literature-derived factors identified in Sect. 2.1 were compared pairwise using a simplified verbal scale ranging from 'less important' to 'more important'. These judgements were converted into reciprocal numerical values using a reduced Saaty-type scale, where equal importance was coded as 1, slight preference as 3, and stronger preference as 5. For each respondent, the values were entered into a 5×5 reciprocal com-parison matrix, and factor weights were derived using the row geometric mean meth-od by normalising the geometric mean of each matrix row. Group-level weights were then obtained by aggregating corresponding pairwise judgements across respondents using the geometric mean. At the indicator level, respondents allocated a fixed total of fixed total of 100 points across criteria to indicate their relative importance [14]. For each factor, respondents allocated 100 points across the three embedded indicators. The final local indicator weights were then obtained by averaging these allocations across respondents and normalising them within each factor. This hybrid structure was adopted to preserve the comparative strength of AHP, while avoiding an unnecessarily burdensome number of pairwise comparisons at the indicator level.

3 Results and Discussion

3.1 Derived Factors and Indicators from Literature

The reviewed literature revealed a consistent set of shortcomings. Stock-based studies are effective at quantifying resource magnitude and locating future flows, but weak at aiding higher-level circular alternatives [15]. Documentation and material/component passports work help identify what reuse decisions depend on, while also exposing how fragmented and incomplete data remains in practice [16]. Spatial circularity studies further show that access, land use, resource proximity and storage determine whether circular flows are even feasible, whereas transport-agency work makes clear that circular projects in infrastructure must still prioritize functional safety and timely operational deliverability [17].

Together, these shortcomings point to five screening questions: candidate credibility, harvestability, operational disruption, regional uptake potential, and environmental or regulatory feasibility, which were the backbone behind factor development (Table 1).

Table 1. Derived factor structure and embedded indicators

Factor	Gap addressed in the literature
F1. Supply readiness and remaining value	Stock visibility does not show whether an asset is a credible reuse candidate
F2. Harvesting and reverse-logistics feasibility	Recoverability is often discussed without sufficient attention to mobilization and handling conditions
F3 Network disruption pressure and network role	Circular screening rarely integrates infrastructure service criticality and operations
F4 Circular ecosystem and match potential	Asset-level supply does not show whether regional uptake, storage and matching conditions exist
F5 Environmental and regulatory constraints	Circular options are overstated when land and environmental restrictions are not treated as feasibility limits

Supply readiness and remaining value (F1) address the central weakness of stock-based approaches: material quantity alone is a poor basis for prioritization. Francart et al. [14] make this point clear by arguing that municipal inventories based solely on aggregate estimates are insufficient for shifting to reuse decisions, whereas Honic et al. [17] show that digital models become more useful when quantities are linked to richer attribute-level information. The factor, therefore, combines three indicators designed to leverage existing AMS data and close this gap. Material stock magnitude captures whether the bridge represents a meaningful quantitative payoff as a supply source at the screening stage. Condition and restrictions then narrow that supply to bridges whose current state and restriction profile, such as defect flags or load limitations, indicate enough structural integrity to justify follow-up. Documentation readiness reflects whether the basic records needed to credibly assess reuse, including geometry, material specifications, and maintenance history, are available without intensive verification effort. Together, the factor captures whether value, technical plausibility, and informational confidence coexist strongly enough for a bridge to merit further attention.

Harvesting and reverse-logistics feasibility (F2) emerged because reuse fails not only when supply is absent, but also when recovery cannot be organized in space and time. Tsui et al. [18] identify accessibility, land availability, storage needs, and plot size as core spatial parameters for circular operations, while Verga and Khan [19] likewise show that space and land are recurrent barriers because circular activities impose greater temporal and spatial demands than traditional approaches. These insights support a factor centred on mobilization capacity. Distance to interchanges serves as an early accessibility proxy,

near-site staging space indicates whether suitable nearby space exists for temporary laydown and sorting, and typology-based disassemblability captures expected disassembly effort using structural characteristics as a screening substitute for connection-level detail. The factor, therefore, distinguishes conceptually attractive reuse from what can be realistically mobilized.

Network disruption pressure and network role (F3) address a gap that is less visible in building-led circularity research but unavoidable in bridge management. Lange et al. [20] indicate that bridge material flows are shaped by bridge-specific conditions, traffic load, and structural deficiencies, while Madden et al. [16] show that circularity in transport systems must remain aligned with the continued safety and technical function of the network. Even where material value, logistics, and recoverability appear favourable, interventions may still be unrealistic if a bridge is indispensable as a network link or if detours are absent. Demand level therefore approximates disruption pressure through traffic intensity; the functional importance class captures the route's strategic role as a network-criticality signal; and rerouting feasibility reflects whether operational measures such as closures, night work, or detours are realistically available. In this way, reuse potential is assessed not only at the asset level but also in relation to wider system effects.

Circular ecosystem and matching potential (F4) responds to the fact that reuse is not realised by a singular asset alone. GIS-supported territorialization can reveal resource-sharing opportunities by mapping resources and potential interactions. Verga and Khan [19] similarly show that circular activities rely on constellations of depots, warehouses, and collection nodes, and that sustained access to such spaces is itself an enabling condition. This supports a factor concerned with the regional context that can absorb and circulate recovered components. Typology clustering represents matching potential, where similar bridges in short distances increase compatibility and economies of scale; proximity to depots/storage yards captures handling and temporary storage capacity; and proximity to demand centres serves as a screening proxy for whether uptake and project matching are feasible within an acceptable radius. Together, these indicators estimate whether a bridge is embedded in a territorial configuration that can support reuse.

Environmental and regulatory constraints (F5) further function as a feasibility filter for the previous four. Tsui et al. [18] include land-use and environmental suitability among parameters for identifying viable hub locations, while Verga and Khan [19] show that circular ambitions compete with other spatial claims and that land scarcity can suppress otherwise promising practices. Opportunity maps are thus unreliable unless constraint layers are treated as constitutive rather than secondary. For bridge screening, protected area proximity indicates whether the asset lies within or near sites such as Natura 2000, national parks, nature reserves, etc. that can restrict methods and staging. Environmental constraints capture hydrological contexts such as floodplains, water protection areas, riparian buffer zones, etc. that may limit works and temporary storage. While other regulated zones represent additional planning and permitting constraints, including cultural heritage protection areas, designated landscapes, and archaeological zones. Thus, the factor intends to flag where circular action is likely to be delayed, narrowed, or blocked by siting and permitting conditions.

3.2 AHP/Budget Allocation Weights from Expert Surveys

Table 2 presents the final factor weights from group AHP and the local indicator weights from the budget-allocation exercise. Consistency was assessed using Saaty's consistency ratio (CR). For each matrix, the weighted-sum vector was calculated by multiplying the pairwise comparison matrix by the derived priority vector. This was divided element-wise by the priority vector to estimate λmax, after which the consistency index was calculated as $CI = (\lambda max - n)/(n - 1)$. The CR was then obtained by dividing CI by the random index; for a five-factor matrix, $n = 5$ and $RI = 1.12$. A CR below 0.10 is commonly treated as acceptable (Saaty, 1980). Respondent -level CR values ranged from 0.066 to 0.151, while the aggregated group matrix produced a low CR of 0.012. Although some individual responses slightly exceeded the conventional 0.10 benchmark [13], the low group-level CR suggests that the overall weighting pattern remained stable post-aggregation, which is consistent with applied AHP studies reporting somewhat higher inconsistency in individual self-administered survey formats [21].

Table 2. Factor and Indicator Weights

Factors (**AHP**)	Indicators (*Budget allocation*)
Supply readiness and remaining value (**0.276**)	Condition and restrictions (*0.464*); Material stock magnitude (*0.243*); Documentation readiness (*0.293*)
Harvesting and reverse-logistics feasibility (**0.166**)	Distance to interchanges (*0.314*); Near-site staging feasibility (*0.229*); System-level disassemblability (*0.457*)
Network role and disruption pressure (**0.220**)	Demand level (*0.357*); Functional importance class *(0.407)*; Workability/rerouting feasibility (*0.236*)
Circular ecosystem and match potential (**0.204**)	Typology-based matching potential (*0.386*); Proximity to depots/storage *(0.250)*; Proximity to demand centres (*0.364*)
Environmental and regulatory constraints (**0.134**)	Protected area proximity (*0.414*); Environmental constraints incl. water/flood (*0.343*); Other regulated zones overlap/proximity (*0.243*)

Respondent consistency ratios (CR): R1 = 0.147, R2 = 0.087, R3 = 0.066, R4 = 0.151, R5 = 0.106, R6 = 0.112, R7 = 0.129; aggregated group CR = 0.012

The experts placed the greatest overall emphasis on Supply readiness and remaining value (F1), followed by Network disruption pressure and network role (F3) and Circular ecosystem and match potential (F4). This suggests that early screening was understood primarily as a question of whether a bridge is a credible reuse candidate, whether intervention can be accommodated within the transport network, and whether the surrounding regional context is favorable to circular flows. Among factors, the highest local weights

were assigned to condition and restrictions in F1, system-level recoverability in F2, functional importance class in F3, typology clustering/matching potential in F4, and protected area overlap/proximity in F5. Overall, the results reinforce that promising circular candidates cannot be distinguished solely by material quantities, but require simultaneous consideration of asset readiness, recoverability, network role, and regional matching conditions.

4 Conclusion

This paper addressed the current gap between circular-economy ambition in infrastructure management and the limited availability of practical tools for early portfolio-scale decision support. While component reuse is widely recognised as a high-value circular strategy, its implementation in bridge management remains difficult because decisions are often made too late, relevant information is fragmented, and operational, logistical, and contextual constraints are rarely considered together at the screening stage. In response, this study developed an indicator-based regional screening approach that translates reuse-relevant considerations into a compact set of weighted factors and indicators, operationalised primarily using typical asset management and GIS data. The study combined a PRISMA-guided scoping review with an expert-weighting exercise using hybrid AHP and budget allocation. The resulting structure showed that experts prioritised supply readiness and remaining value most strongly, followed by network -related and ecosystem-related considerations, while harvesting feasibility and environmental or regulatory constraints were also retained as important parts of the screening logic. Taken together, the results suggest that promising circular candidates cannot be identified solely from material quantities, but require simultaneous attention to asset condition, recoverability, network role, and regional matching context. This combination will be applied and validated for a bridge stock dataset from the Motorway network of Croatia as a continuation of the study. Overall, the approach provides a practical first step toward moving circularity from a general ambition to a more operational, targetable decision problem in infrastructure planning.

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Whole Life Carbon Assessment as a Tool for Urban Climate Action

Roberto Giordano(✉), Jacopo Andreotti, and Alice Masoero

Department of Architecture and Design, Politecnico di Torino, Turin, Italy
roberto.giordano@polito.it

Abstract. The mitigation of building-related greenhouse gas emissions (CO_2eq) is now recognised as a prerequisite for achieving long-term climate objectives. Several European countries and local communities are taking action to implement the Whole Life Carbon (WLC) vision and make it practical, enabling the assessment of building life-cycle emissions. The paper presents a simplified, standardised methodology for assessing WLC in building projects, developed as part of scientific research carried out for an Italian Municipality. The proposed framework aims to support the systematic accounting and reporting of CO_2eq emissions associated with new construction and renovations. The methodology is grounded in the Life Cycle Assessment standard and consistent with European standards and policy measures, including EN 15978, EN 15804, the Level(s) framework, and the Energy Performance of Buildings Directive recast (EPBD, EU 2024/1275). It focuses on selected life cycle modules: production (A1–A3), construction (A4–A5), use (B4, B6), and end-of-life (C2–C4). A twofold application is defined, encompassing a WLC evaluation at both the early design phase and the as-built report, utilising different data and quality levels (e.g., material generic data vs. product-specific data).

The paper outlines a simplified WLC framework to enhance comparability and decision-making in municipal contexts. Since the framework has not yet been validated through real case studies, the contribution describes the methodology underlying the simplified WLC assessment. This methodology represents the basis for a subsequent research phase focused on the application and validation of the framework in real case studies.

Keywords: Whole Life Carbon · Embodied Carbon · Operational Carbon · Life Cycle Assessment · Building standard

1 Introduction

The decarbonisation of the built environment is widely recognised as a critical component of global climate mitigation strategies. Buildings account for a substantial share of global greenhouse gas emissions, due to both operational energy use and embodied emissions associated with construction materials and processes [1, 2].

Historically, since Regulation 2018/1999, policies aimed at reducing the environmental impact of buildings have primarily focused on operational energy use [3]. However,

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improvements in building energy efficiency are progressively increasing the relative importance of embodied emissions associated with materials, construction activities and end-of-life processes. Consequently, the concept of Whole Life Carbon (WLC) has emerged as a comprehensive framework for assessing the total greenhouse gas emissions associated with buildings throughout their life cycles [4, 5].

WLC assessment builds upon the methodological principles of Life Cycle Assessment (LCA) and is increasingly supported by international standards and European policy initiatives. In particular, the European standards UNI EN 15978 and UNI EN 15804 provide a consistent methodological basis for calculating the environmental impacts of buildings and construction products [6, 7]. From the policy standpoint, the Level(s) framework and the fourth recent recast of the Energy Performance of Buildings Directive (EPBD IV) require assessing the Global Warming Potential (GWP) across the entire building life cycle, accounting for CO_2-equivalent (CO2eq) emissions [8, 9].

Finally, some national and local initiatives have been introduced. In Italy, the Municipality of Milan adopted the "Piano Aria e Clima" (Air and Climate Plan) in 2021 to reach climate neutrality by 2050 [10]. At the same time, the recently introduced national standard UNI 11973:2025 highlights the relevance of decarbonising buildings. It sets out guidelines and procedures for WLC accounting [11].

In this context, there is a growing need for shared methodologies that enable designers to quantify carbon emissions effectively. This paper presents the development of "Operational Instructions" for a **simplified Whole Life Carbon** (WLC) **framework** intended for integration into urban planning and construction permitting processes. Aligned with the aforementioned standards and frameworks, as well as the national initiative *Tools for Decarbonisation* [12, 13], the proposed approach defines a practical and consistent tool for evaluating building-related emissions in accordance with international methodologies. Finally, the framework builds upon LCA principles while introducing methods that enable its application during different phases of the building process.

2 The Simplified Whole Life Carbon Framework

2.1 Definition and Indicators

The simplified WLC framework aims to quantify greenhouse gas emissions from buildings throughout their life cycles. According to UNI EN 15978 [8], the life cycle of a building can be divided into several modules covering the Production of construction materials, Construction processes, Use, and End-of-Life scenarios (see Fig. 1).

The simplified WLC framework is the sum of two main components:

- **Embodied Carbon (EC):** CO_2eq emissions from Production (A1–A3), Construction (A4–A5), Replacement (B4), and End-of-Life (C2–C4).
- **Operational Carbon (OC):** CO_2eq emissions related to energy needs during the Use of the buildings (B6) for heating, domestic hot water, cooling, lighting, and movement.

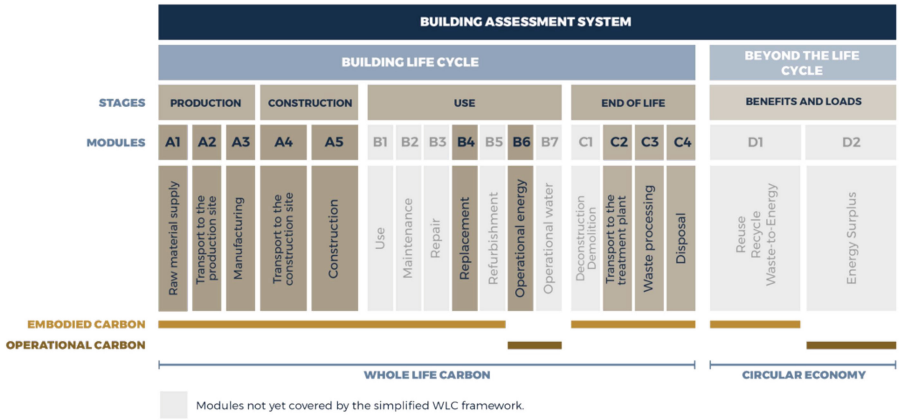


Fig. 1. Stages and modules covered by the WLC simplified framework.

2.2 Scope and Boundaries

The simplified WLC framework targets residential, office, school, healthcare, recreational, commercial, and sports buildings, excluding uses and typologies not covered by EPBD or the local building code.

The framework is designed for new buildings; however, with the appropriate selection of building elements and information on mechanical and electrical services, the method can also be used for buildings undergoing major retrofits.

The Functional Unit adopted is: $kgCO_2eq/(m^2$ HFA*year), where Heated Floor Area corresponds to the internal floor area of spaces served by the building's heating/cooling services.

The methodology also includes declared units, used in the accounting process for some modules. In this paper, a declared unit is represented by the Gross Floor Area (GFA), calculated in accordance with the EC for construction and installation processes (ECA5). The methodology is designed to support two main design and building processes:

- **Early Design.** The WLC framework provides a simplified approach to calculations, using generic datasets. This phase aims to support designers in comparing alternative design options and in identifying strategies to reduce embodied and operational carbon.
- **As-Built**. At this phase, calculations rely on more detailed information, including product-specific environmental data and updated quantities.

This two-step approach enables a progressive improvement of carbon estimates while ensuring consistency between design decisions and final reporting.

The reference period of the study (RSP) is set to align with the lifespan of buildings as defined in the main international standards, particularly Level(s) [8].

2.3 Modules and Calculation

The simplified WLC framework follows a structured procedure to ensure consistency across different building typologies:

- **Inventory Analysis:** material masses collection based on the "Design-as-Built (DaB)" project information.
- **Emissions Mapping:** assignment of emission factors (Generic or Specific/EPD) for each material to the accounted modules and stages.
- **Impact Calculation:** Application of the formulas across defined modules.

In the early design phase, emission factors are derived from generic datasets and literature-based values. In contrast, during the as-built phase, they are progressively replaced, where available, with product-specific data from Environmental Product Declarations (EPDs) to improve data quality and representativeness. Given the simplified nature of the framework, the results may be affected by uncertainty related to data quality and by assumptions concerning, among others, transport distances, replacement cycles, and end-of-life scenarios; these aspects will be examined through sensitivity analyses in the subsequent validation phase on real case studies."

The impact calculation refers to a defined number of life-cycle modules from UNI EN 15978, focusing on those assumed most relevant to municipal-level carbon accounting. Some modules were not considered because they were deemed difficult to account for. More specifically, priority was given to modules that can be accounted for using databases, certifications, and declarations (e.g., Environmental Product Declaration), or modules for which it is possible to establish assumptions compatible with local construction processes (e.g., average distances between the production site and the building construction site).

A1–A3 (Production): The modules account for raw material extraction and manufacturing. Calculations start from the DaB materials mass, adjusted by a production correction factor to account for site waste. If no specific information is available, a 9% value may be applied to all materials. For wood-based materials, the methodology accounts for biogenic carbon as a credit, provided it is not incinerated or landfilled at the End-of-Life (EoL).

Equation (1) defines the production $EC_{A1–A3}$:

$$EC_{A1-A3} = \sum_{J=1}^{n} \left[M_j \times f_{A1-A3,j} \times \left(1 + w_j\right) \right] \tag{1}$$

Where:

M_j = mass of the j-th material (kg)
$f_{A1–A3,\,j}$ = emission factor of the j-th material ($kgCO_2eq/kg$)
w_j = production factor of the j-th material (%)

A4 (Transport): The module uses standardised emission factors to estimate the impact of material transportation. Equation (2) defines the transport EC_{A4}:

$$EC_{A4} = \sum_{J=1}^{n} \left(M_j \times dj \times f_{trans,j} \right) \tag{2}$$

Where:

M_j = mass of the j-th material (kg)
dj = distance for transport from the factory gate to the construction site of the j-th material (km)
$f_{trans,\,j}$ = transport mode emission factor of the j-th material ($kgCO_2eq/km$)

A5 (Installation/Construction): The module accounts for emissions from on-site assembly and the management of construction waste. The installation is estimated via standardised factors based on the building's Gross Floor Area (GFA) or specific site equipment data. Equation (3) defines the Installation/Construction EC_{A5}:

$$EC_{A5} = GFA \times k_{A5} \tag{3}$$

Where:

GFA = Gross Floor Area (m^2)
k_{A5} = installation emission factor ($kgCO_2eq/GFA$)

B4 (Replacement): The module considers the estimated service life of components. Materials with a lifespan shorter than the RSP must be replaced, thereby increasing EC. "Roundup" is an operation that takes a number and rounds it to the nearest integer that is greater than or equal to that number. For instance, in the roundup, the result is 3, even though 2.5 is exactly in the middle; it always rounds up to the next whole number. Equation (4) defines the number of replacements and Eq. (5) the CO_2eq emissions released by the new materials installed EC_{B4}:

$$N_j = ROUNDUP\left(\frac{RSP}{SL_j} \right) \tag{4}$$

Where:

roundup = a function that increases a number to the nearest whole number
RSP = Reference Study Period (year)
$SL_{\,j}$ = Service Life of the j-th material (year)

$$EC_{B4} = \sum\nolimits_{J=1}^{n} \left[\left(EC_{A1-A3,j} + EC_{A4,j} \right) \times N_j \right] \tag{5}$$

Where:

$EC_{A1–A3,\,j}$ = emissions released from the j-th material's Production, see Eq. (1) ($kgCO_2eq$)
$EC_{A4,\,j}$ = emissions released from the j-th material's Transport to the construction site, see Eq. (2) ($kgCO_2eq$)
N_j = number of replacements of the j-th material within the RSP (number)

B6 (Operational Energy): The module is based on the energy performance certificates and predicted energy demand for the building's operation (e.g. Energy Performance Certificate). Equation (6) defines the Operational Carbon OC_{B6}:

$$OC_{B6} = \sum_{K=1}^{n} \left(Q_{B6,k} \times f_{B6,k}\right) \tag{6}$$

Where:

$OE_{B6,\,k}$ = energy needs of the building, including heating-cooling, ventilation, lightning (kWh/year)
$f_{B6,\,k}$ = emission factor of the k-th energy carrier ($kgCO_2eq/kWh$)

End-of-Life (C2–C4): These modules include waste transport (C2), waste treatment (C3), and final disposal (C4). The methodology requires determining $kgCO_2eq$ for modules C2–C4 by applying emissions factors to the waste mass. This mass is calculated by considering the volumes of waste produced by the Installation/Construction (A5), the Replacement (B4), and the building's EoL (C). Equation (7) defines the total waste mass:

$$M_{waste,j} = \sum_{J=1}^{n} \left[\left(M_j \times w_j\right) + \left(M_j \times N_j\right) + M_j\right] \tag{7}$$

Where:

M_j = mass of the j-th material (kg)
w_j = production factor of the j-th material (%), see Eq. (1)
N_j = number of replacements of the j-th material within the RSP (number), see Eq. (4)

Based on the waste mass, the transport to the treatment plant (C2) is calculated by assuming a fixed distance of 30 km. The CO_2eq emissions can be figured out by applying Eq. (2). At the same time, the waste processing (C3) and final disposal (C4) are performed together. It is based on a conservative EoL scenario of 30% disposal and 70% recycling, in line with EU waste policy and plans. Equation (8) defines the $EC_{C3–C4}$:

$$EC_{C3-C4} = \sum_{J=1}^{n} \left(M_{waste,j} \times 0,3\right) \times f_{C3-C4\ \mathrm{rec},j} + \left(M_{waste,j} \times 0,7\right) \times f_{C3-C4\ \mathrm{dis},j} \tag{8}$$

Where:

$M_{waste,\,j}$ = mass of the j-th waste (kg)
$f_{C3–C4\ rec,\,j}$ = emission factor of the j-th waste recycled ($kgCO_2eq/kg$)
$f_{C3–C4\ dis,\,j}$ = emission factor of the j-th waste landfilled ($kgCO_2eq/kg$)

2.4 The Total Whole Life Carbon

The total WLC building is the sum of EC and OC contributions, normalised to HFA and RSP. Equation (9) defines the WLC:

$$WLC = \frac{\sum(EC_{A1-A3} + EC_{A4} + EC_{A5} + EC_{B4} + OC_{B6} + EC_{C3-C4})}{HFA \times RSP} \quad (9)$$

Where:

$EC_{A1–A3}$ = emissions from Production ($kgCO_2eq$)
EC_{A4} = emissions from Transport of material to the construction site ($kgCO_2eq$)
EC_{A5} = emissions from Installation/Construction ($kgCO_2eq$)
EC_{B4} = emissions from Replacement ($kgCO_2eq$)
OC_{B6} = emissions from Operational Energy ($kgCO_2eq$)
EC_{C2} = emissions from Transport of waste to the treatment plant ($kgCO_2eq$)
$EC_{C3–C4}$ = emissions from the EoL scenario of waste ($kgCO_2eq$)
HFA = Total square meters of Heated Floor Area (m^2)
RSP = Reference Study Period (50 years)

A crucial step in the research is setting appropriate benchmarks for assessing the results achieved by the different buildings. Owing to ongoing testing of the methodology, a preliminary step involved setting an initial threshold value of 800 $kgCO_2eq/m^2$HFA*year for residential buildings, and 900 $kgCO_2eq/m^2$HFA*year for other uses (e.g. offices, schools, etc.) based on recent research conducted in Mediterranean EU countries [14, 15]. This value can be understood as an intermediate milestone in long-term carbon-reduction scenarios.

3 The Whole Life Carbon for Urban Climate Action

The simplified framework is designed to enable the integration of WLC assessment into urban climate action.

First and foremost, it is intended to provide a user-friendly, accessible framework for non-LCA experts, built on databases, certifications, and declarations available online, many of which are open source. The assumptions used to account for certain stages and modules are based on international standards and studies.

Second, by adopting a consistent calculation and reporting structure, the simplified framework is expected to improve the comparability of building projects by establishing a methodology for calculating and reporting emissions; the latter is particularly relevant for municipalities seeking to monitor the carbon performance of construction activities within their territories.

Third, the use of simplified data structures facilitates integrating WLC assessment into early design stages, enabling designers to evaluate the carbon implications of alternative materials and construction strategies.

Finally, the framework may support the future integration of EC and OC metrics into municipal climate policies and support the development of regulatory instruments to reduce building-related emissions.

4 Conclusion

The simplified WLC framework provides a pragmatic yet rigorous tool for urban climate assessments. Nevertheless, the practical application of LCA-based methods in design and policy contexts remains challenging due to their complexity and data requirements. Data availability and consistency remain critical issues, particularly for product-specific environmental data. In addition, future developments may benefit from integrating digital tools such as Building Information Modelling (BIM) and digital twins to enable automated data exchange.

The methodology has not yet been validated through applications to real buildings. At this stage, preliminary analyses have been conducted on representative building archetypes to test the internal consistency of the calculation structure and to support the definition of initial thresholds. The empirical validation of the framework through applications to real building cases constitutes the next phase of the research.

Future research targets include applying the WLC framework to a sample of different building types; this will enable the establishment of a benchmark and, subsequently, the development of a rating system comparable to the one currently used to assess energy performance.

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Framework for Multi-Cycle Assessment in Circular Construction

John van Oorschot(✉), Joana Gonçalves, Francesca Vanoverberghe, and Wai Chung Lam

Vlaamse Instelling voor Technologische Onderzoek (VITO)/EnergyVille, Boeretang 200, 2400 Mol, Belgium

john.vanoorschot@vito.be

Abstract. Efforts to promote material reuse and selective deconstruction in the built environment increasingly rely on assessment tools to inform design, demolition, and policy decisions. However, current evaluation practices often fail to deliver coherent and decision-relevant insights across the building lifecycle. Circularity indicators tend to prioritize material cycling without adequately capturing environmental or value-retention impacts, while lifecycle assessment (LCA) remains rooted in single-cycle, linear logic. As a result, circularity and LCA frequently operate in parallel, producing fragmented or conflicting signals for decision-makers. Assessment outcomes are shaped by data availability, assumptions, and tool-specific structures. Data fragmentation, limited traceability of as-built conditions, and non-harmonised practices undermine comparability and confidence in results. These challenges are compounded by the fragmented construction value chain, where reuse only materialises when documentation aligns with market demand, regulatory conditions, and timing. This paper presents the development of a framework that addresses these limitations by linking environmental performance, circular strategies, and value retention across multiple lifecycles and building scales. Designed as a hierarchical structure, it ties together existing tools, indicators, and datasets within a shared logic. It integrates data from building inventories, circularity indicators, and LCA-based assessments, while remaining sensitive to decision contexts and stakeholder roles. By operationalising lifecycle thinking and coordinated decision-making, the framework clarifies actor involvement at distinct lifecycle phases and the basis of information use. Structuring assessment around purpose-driven, multi-cycle logic supports robust decision-making and provides a foundation for material catalogues and reuse marketplaces through transparent, scenario-based assessments linking environmental performance with value retention.

Keywords: Multi-Cycle Assessment · Circular Construction · Material Reuse · Life Cycle assessment · Decision-Making · Deconstruction

1 Introduction

The built environment is undergoing a pivotal transformation driven by the twin transition towards digitalization and sustainability. A key challenge within this transition is enabling multi-cycle management of building elements, components, and materials

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to substantially reduce demolition waste, greenhouse gas emissions, and risks related to hazardous substances. Adopting a multi-cycle perspective enables the assessment of building elements and materials beyond a single linear life cycle, supporting cascading reuse, refurbishment, and recovery scenarios across successive use phases and preventing premature value loss [1, 2]. Improving access to reliable data across building life cycles is essential to unlock these benefits and to support the construction sector in delivering environmental gains, societal value, and economic opportunities.

Despite growing interest, significant methodological gaps persist. The sector is overwhelmed by a plethora of circularity tools which tend to be applied in isolation and without a clear stipulation about what and how they indicate circularity of buildings or its assets. Quantitative assessments remain largely carbon-centric, a phenomenon described as *carbon tunnel inertia* [3], where a narrow focus on CO_2 emissions obscures broader environmental impacts, resource depletion, and long-term value retention. Circularity assessments, in turn, are frequently disconnected from environmental and economic evaluation frameworks, limiting their practical applicability for end-of-life decision-making. This fragmentation presents a critical barrier for stakeholders, particularly demolition contractors and users of reclaimed construction elements, who must align circular ambitions with environmental performance and economic feasibility under real-world constraints.

To address these gaps, the paper asks: How can a multi-cycle perspective be operationalized within an integrated assessment framework that captures environmental and economic implications in alignment with real-world selective deconstruction processes? This paper presents the development of an integrated multi-cycle assessment framework designed to support evidence-based decision-making for building end-of-cycle scenarios. Rather than introducing a new aggregated sustainability scoring system, this framework provides a structured approach to define and evaluate multi-cycle scenarios, enabling consistent evaluation of circular strategies and positioning buildings as material banks for future use. In doing so, it addresses the disconnect between environmental assessment, economic valuation, and circularity assessment, contributing to a practical and scalable approach to advancing sustainable and circular management in practice.

2 Theoretical Background

Selective deconstruction refers to the act of taking a building apart and recovering the value embedded in its assets, i.e. building elements, components and materials, using different demolition strategies, methods, technologies and workflows [4–6]. The current landscape of circular deconstruction guidance frameworks provides an important foundation for moving beyond conventional demolition. Nonetheless, several gaps hinder their effectiveness and wider adoption. A key issue is the fragmentation and diversity of existing frameworks and indicators, resulting in inconsistencies and limited interoperability [7]. Furthermore, most frameworks lack a strategic decision-support structure that systematically integrates the full spectrum of circular economy strategies in accordance with the established priority ladder (R-strategies). This shortcoming is particularly evident in the absence of a clear methodology for decomposing construction objects from the building level down to elements, components, and materials. At the core of these

limitations lies the absence of a shared structuring logic that connects inventories, circularity indicators, economic valuation, and environmental assessment across scales. Addressing these limitations by harmonizing frameworks, embedding standardised criteria, and developing integrated decision-support systems, could significantly enhance the effectiveness and adoption of selective deconstruction.

Building inventories form the empirical backbone of selective deconstruction. A material inventory systematically documents the elements and materials present in an existing building and their associated characteristics. By identifying quantities, characteristics, and timing of availability, inventories enable matching supply and demand and support value retention. Without reliable and structured inventories, multi-cycle assessment remains theoretical rather than operational.

Multi-cycle lifecycle application of building assets starts from the premise of maintaining the value of materials, components, and buildings for as long as possible through circular strategies like reuse, repair, refurbishment, and recycling, contrasting the traditional linear "take-make-waste" model. However, circularity is often reduced to waste management and end-of-life considerations, lacking integration with environmental and economic assessment [8, 9]. In response, multi-cycle life cycle frameworks should adopt an explicit multi-cycle perspective, embedding circularity within structured environmental and economic assessments rather than treating it as a separate set of indicators.

While LCA remains the most accepted methodology for assessing environmental impacts, when circularity is introduced, it often remains external to LCA, addressed through separate indicator sets rather than being structurally embedded within the assessment logic. A multi-cycle perspective therefore requires embedding circularity within LCA through complementary indicators that capture cascading scenarios and the feasibility of higher R-strategies, for instance via disassembly [10, 11].

To operationalise this perspective, complexity must be reduced through structured and gradual analysis of circularity indicators. The following four hierarchical levels of analysis have been defined: building, building elements, building components, and building materials. These levels correspond to Brand's shearing layers, highlighting differentiated lifespans and replacement cycles, which are essential for multi-cycle value retention [12].

The hierarchy of R-strategies is fundamental to defining the multi-cycle circularity scenarios at each hierarchical level. The R-strategies are often presented in a sequential ladder from R0 (Refuse) to R9 (Recovery), prioritising actions that preserve embedded value and prevent downcycling. From a multi-cycle perspective, materials need to be kept in the circular loop by making them available again to use within a building, therefore maximizing value retention. Multi-cyclical application begins with determining whether a certain element, component or material is worth reclaiming based on its residual value. Residual value comprises residual technical (remaining functional capacity), economic (remaining monetary worth), and environmental value (avoidable embodied impact through reuse). Reclaim potential translates residual value into operational feasibility. End-of-life treatment depends not only on residual value but also on disassembly potential, defined as the ability to remove elements without compromising

surrounding objects [13]. Residual value and disassembly potential determine whether higher R-strategies can be realistically implemented.

Together, these concepts (hierarchical layers, R-strategy prioritisation, residual value assessment, disassembly potential, and structured inventories) establish the theoretical foundation for operationalising a multi-cycle assessment logic. They clarify how environmental and economic evaluation must be embedded within a layered and scenario-based decision structure that will be further detailed in the following sections.

3 Methodology

For the development of the multi-cycle life cycle framework, a design science approach (DSA) was followed [14, 15]. This approach focuses on the creation and evaluation of purposeful, innovative artifacts to solve complex, real-world problems. It emphasises both practical relevance and scientific rigour, bridging the gap between theory and application. This study followed five successive stages in developing the conceptual framework:

1. Relevant environmental and circularity concepts were identified based on literature on assessing sustainability and circularity in the built environment.
2. The decision context was identified and translated into the basic hierarchical structure of the framework.
3. To guide evidence-based decision-making on which R-strategy to pursue, key sustainability and circularity indicators were integrated in the framework in accordance with relevant standards and frameworks. Conditional indicators regarding value retention and reclaim potential were added.
4. The conceptual framework in the format of a flow diagram annex decision tree was designed.
5. For internal validation and refinement an expert meeting to validate and improve the conceptual design of the multi-cycle framework was conducted.

4 The Integrated Multi-Cycle Framework

Building on the previous theoretical context, the proposed framework is operationalised as a hierarchical, data-driven decision tree guiding selective deconstruction planning. Rather than providing a final sustainability score, the framework structures decision-making to define feasible multi-cycle scenarios and link them to appropriate selective deconstruction strategies. The framework constituents seven conceptual building blocks, positioning circularity indicators at the core and linking them to hierarchical levels, layers of Brand, R-strategies, reclaim potential, value retention, and inventory frameworks, within a unified decision logic. Through this structure, environmental assessment (LCA), life cycle costing (LCC), and circularity indicators are not treated as parallel tools but are embedded within a single decision logic aligned with established European standards and policy frameworks.

The multi-cycle framework is structured as a hierarchical decision logic across four levels: Building, Element, Component, and Material. As illustrated in Fig. 1, each hierarchical level follows a comparable decision sequence: (1) inventory and identification,

(2) assessment of physical condition, (3) evaluation of residual value, (4) analysis of disassembly potential, and (5) selection of an appropriate R-strategy. This recurring structure ensures consistency while allowing level-specific priorities to emerge.

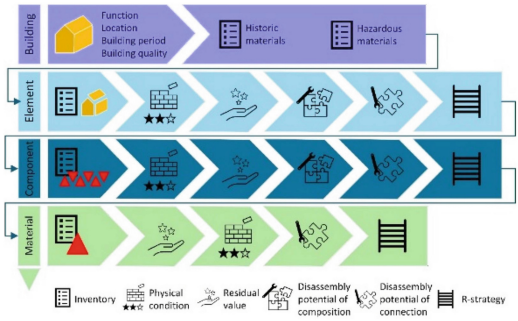


Fig. 1. The basic design of the Multi-Cycle Life Cycle Framework. For the detailed design: DISCOVER Decision Tree V2 - Miro

It begins by contextualising the building from which the material compositions and the building techniques can be deduced. The next step is to obtain an overview of which parts of the building are to be preserved for reasons of safety, heritage and/or community significance. Next, the framework challenges the necessity of demolishing the remaining. It explores whether a new project could be realised within the existing structure and therefore examines opportunities for waste reduction during design of the new project, targeting the highest R-strategies. Only when demolition is confirmed as unavoidable does the logic proceed to the lower hierarchical levels.

The element and component levels are structured identically. First, the tree questions whether the element or component in question is worth reclaiming, by assessing its residual technical (RTV), residual economic (REV) and embedded environmental (EEV) value. This tri-dimensional assessment determines whether higher R-strategies are technically and environmentally justifiable. If the analysis has a negative outcome, the tree transfers to a cascading level in the hierarchy. If the analysis has a positive outcome, the element's or component's DP is evaluated. If this component or element is fully integrated into the building or other elements or components, the tree proceeds to a cascading level. If it is modular, the tree continues to evaluate the DP of its connections, resulting in the appropriate EOL R-strategy.

Once it has been evaluated whether EOL treatment is possible on a higher hierarchical level, the material level comes into play. On the material level, the reclaim potential is first analysed using the REV and EEV of the material, instead of starting with an evaluation of its RTV, as in practice, the REV is the dominant factor to determine feasibility. If the material is evaluated as worth saving, the DP of the connections is assessed to determine the optimal EOL treatment based on the dismantling techniques required. At this level, economic feasibility, environmental benefit, and reclaim potential converge to refine the recommended recovery pathway.

Once completing the decision tree, as a key outcome, several evidence-based multicycle scenarios are being derived, indicating how a building and its subsequent assets

could be retained, which subsequently can be used to conduct LCA, LCC, circularity, sufficiency and/or sustainability assessments.

The operationalisation of the decision tree is subject to several boundary conditions related to data availability, valuation logic, market feasability, and technical constraints. The process of inventorying an existing building is time-consuming and costly. Currently, these inventories are often drafted manually and are therefore prone to errors and subjectivity. In addition, no standardised framework exists that dictates their format. To tackle this, different levels of inventories are introduced in the decision tree, namely: element inventory, component inventory and material inventory. The level of detail within these inventories intensifies with each hierarchical level. This tiered approach prevents excessive data collection at the outset and aligns the level of analysis with the decision context.

A second boundary condition concerns the evaluation of residual value. This is assessed as a balance between the residual technical, economic and embedded environmental value. Today, a demolition contractor starts with an economic evaluation to determine the reclaim pathway of DW, applying a lowest-cost approach. The costs related to environmental impacts, however, are currently not reflected in the economic value. This results in most materials being evaluated as waste, ignoring their reclaim potential. To counterbalance this bias, the framework treats embedded environmental value as equal to the economic value in determining feasible recovery pathways.

Finally, the application of disassembly potential requires careful interpretation. From an EOL perspective of a demolition contractor, an order of importance can be identified that differs for each hierarchical level. Accordingly, the framework adapts the weighting of disassembly criteria depending on the scale of analysis, ensuring that technical feasibility is assessed in relation to realistic deconstruction pathways.

5 Discussion and Conclusion

This paper explored the development of a guidance and assessment multi-cycle life cycle framework to support evidence-based decision-making for circular and sustainable end-of-life (EOL) strategies for buildings scheduled for decommissioning. The framework intends to guide the formulation of selective deconstruction plans that prioritise value retention of building systems, components, and materials thereby reducing potential environmental impacts. The framework establishes a structured approach to evaluating residual value, disassembly potential, and the applicability of different R-strategies across multiple life cycles, thereby bridging theoretical insights with practical requirements in selective deconstruction.

The developed framework provides a conceptual foundation for operationalising multi-cycle assessment in demolition practice. The current framework offers a replicable structure that guides evidence-based decision-making throughout the deconstruction process. In doing so, it lays the groundwork for a more systematic integration of circularity, life cycle thinking, and economic value assessment in the future of sustainable deconstruction. The multicycle scenarios derived from the framework can be used for quantitively and qualitative LCA, LCC, circularity, sufficiency and/or sustainability assessments. Because rooted in systematically derived scenarios avoiding narrowly set

boundary conditions these assessments are less susceptible to "burden shifting", one of the main methodological issues and critique associated with quantitative LCA and LCC studies [16, 17].

The decision tree is not free of limitations. First, the conceptual framework is not yet validated in its operational context. Specifically, greater clarity is needed regarding the timing of decisions in the deconstruction planning process, namely, which questions should be addressed at which stage, who is responsible for making these decisions, and who bears accountability for their outcomes. Second, the decision tree does not sufficiently differentiate between micro- and macro-economic effects [18, 19]. The framework is primarily designed around micro-economic considerations at the company or project level (e.g., contractors, architects, or individual construction projects). In contrast, macro-economic factors, such as market dynamics, sector-wide investment patterns, and regulatory influences, are largely outside its current scope. Future work could research the effect of market dynamics and public perception on the outcome of the decision tree. Taken together, testing the framework in real demonstrator projects will serve to assess the framework's robustness and effectiveness across a range of real-world scenarios, understanding what needs to be assessed, by whom, and when.

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Circular Economy Measures: Uptake Capacity and Impact Across EU Member States

Giovanna Cassavia[1], Nicolas Alaux[1], Marcella Ruschi Mendes Saade[1], Giulia Pristerà[2], Karen Allacker[2], and Alexander Passer[1(✉)]

[1] Working Group Sustainable Construction, Institute of Structural Design, Graz University of Technology, Technikerstraße 4, 8010 Graz, Austria
alexander.passer@tugraz.at

[2] Department of Architecture, Faculty of Engineering Science, KU Leuven, Leuven, Belgium

Abstract. Circular economy (CE) measures complement operational energy efficiency as a key strategy to reduce building and construction greenhouse gas (GHG) emissions, yet EU Member States' adoption capacities remain unclear. Using PULSE-EU, a building stock model representing the EU27, this study assesses Europe's uptake potential for six specific CE measures and their life cycle GHG mitigation impact considering both operational and embodied emissions. The assessed measures are: (i) reduction of average living area per person, (ii) building service-life extension through renovation, (iii) vacancy reduction, (iv) component/material reuse, (v) increased recycling, and (vi) increased on-site waste sorting. Socio-economic constraints are integrated to estimate realistic national CE uptake capacities. Under maximum diffusion, these measures collectively achieve 147 $MtCO_2e$ reductions by 2050, an 18% decrease from 2020 levels across EU27 embodied and operational emissions. Average living area per person and vacancy reduction emerge as primary mitigation levers, followed consistently by renovation-driven service-life extension, despite regional variations. Reuse, recycling, and waste sorting contribute modestly when assessed individually, but are important enhancers of secondary material flows. The assessment ranks CE measures by their national mitigation potential and highlights countries offering the greatest contributions. Findings emphasize the need for coordinated CE deployment that leverages CE measure's synergies while addressing local implementation barriers.

Keywords: building stock · circularity · renovation · GHG mitigation · life cycle assessment (LCA)

1 Introduction

European buildings and construction are among the world's most resource- and emission-intensive sectors, responsible for 37% of global energy-related CO_2 emissions, 50% of raw material consumption, 40% of waste generation, and 40% of material use through construction and demolition activities [1]. With the European Union (EU) targeting climate neutrality by 2050, transforming building lifecycles is urgent.

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Climate mitigation policies have mainly focused on operational energy efficiency through better insulation, heating systems, and renewable energy integration, as seen in successive Energy Performance of Buildings Directive iterations [2]. These measures successfully reduced EU building GHG emissions by 43% between 2005–2023. However, embodied emissions remain largely unaddressed, comprising over 25% of 2022 building emissions and projected to grow without intervention [3].

Circular economy (CE) measures are increasingly recognized as essential complements to operational efficiency, moving beyond linear "take-make-dispose" models. CE strategies reduce primary material demand through three core principles: narrowing resource flows (efficiency improvements), slowing resource loops (extended service life and intensified use), and closing material cycles (recycling and reuse) [4]. Buildings offer the highest CE mitigation potential after agriculture and food systems, with global savings potential reaching 6.8 $GtCO_2e$ by 2050 through efficient design, space optimization, service-life extension, component reuse, and waste reduction [5].

While recent literature increasingly links CE strategies to climate mitigation, comprehensive EU-wide assessments remain scarce due to inconsistent modeling approaches [3]. Implementation capacity varies significantly across EU Member States, influenced by economic development, building stock characteristics, construction industry maturity, policy frameworks, and socio-cultural factors [6]. Previous studies typically examined single countries with limited CE measures and minimal socio-economic constraint integration [7].

This study addresses these gaps by systematically evaluating six key CE measures' GHG reduction potential across all EU27 Member States from 2020 to 2050, incorporating national adoption capacities for policy-relevant insights.

2 Methodology

2.1 Building Stock Model

PULSE-EU is an open-source building stock modeling framework designed to quantify the environmental impacts, particularly GHG emissions, of the EU27 building stock from 2020 to 2050 [8]. It enables exploration of prospective scenarios, including various Carbon Reduction and Removal Strategies (CRRS), by assessing mitigation potentials and national adoption rates over time [9, 10].

The model employs a bottom-up, archetype-based methodology that represents the heterogeneous EU building stock through 15,026 archetypes. These are defined by key parameters such as building types, construction periods, materials, technical installations, and energy performance levels [11]. Impacts are assessed through the upscaling of archetypes to the stock-level and incorporation of macro socio-economic limitations such as energy system transitions, manufacturing processes, policy interventions, population growth, demolition/renovation/new construction rates, and reuse practices [12].

PULSE-EU integrates two complementary components: material flow analysis (MFA) and prospective life cycle assessment (LCA). The MFA module dynamically tracks material flows through new construction, renovation and demolition, providing

the base for evaluating CE measures and their material loops influence. The LCA component, aligned with the EN 15804 + A2 and EN 15978 standards, uses the MMG-SLiCE LCA framework and Ecoinvent 3.6 database to calculate Global Warming Potential (GWP) across life cycle stages A1–A3 (product), A4–A5 (construction), B1–B7 (use), and C1–C4 (end of life), covering both embodied and operational emissions [13].

2.2 Circular Economy Strategies Assessed

CRRS have been assessed in PULSE-EU through groupings of individual measures [6]. For example, the strategy "Improve material efficiency" can be activated through the measures "Material use optimization in structural design" and "Offsite construction." Here we focus on understanding the impact of individual measures rather than already previously assessed groups of strategies. In between the diverse PULSE-EU measures, we identified and assessed 6 of them which are aligned with CE principles: (i) reduction of average living area per person, (ii) building service-life extension through renovation, (iii) reduction of building vacancy, (iv) reuse of existing building components and materials, (v) increased material recycling and (vi) increased on-site waste sorting. Derived from Alaux et al. [6], Table 1 gives an overview of assessed CE measures, their level of implementation in the model and the PULSE-EU strategies they relate to.

The direct effects of these measures are linked to either the archetype or stock-levels, influencing operational and/or embodied emissions. Measures such as (ii) Building service-life extension through renovation depend on and immediately impact the number of buildings on stock-level. These are therefore directly implemented in the PULSE-EU model. However, the effects of archetype-related measures, such as reducing operational emissions, are captured by adjusting individual archetype's LCA results.

Measures have different uptake levels for 2030, 2040 and 2050, which are influenced by two parameters: capacities and diffusion rates. Capacities differ per country and refer to how intensely and quickly each EU Member State is able to implement a certain measure. Diffusion rates vary by measure and define the percentage of implementation for each, thereby determining the related material flows into the model. Both these parameters are based on local macro socio-economic constraints such as technical feasibility, economic viability, policy support, industry readiness, and social acceptance. Capacities and diffusion rates were determined by following extensive desk research on literature and complemented by interviews with selected stakeholders from the industry and representative institutions. Further information on how capacities and diffusion rates are quantified and validated is available in Alaux et al. (2024) [6] and in the "Strategies" file under the associated GitHub repository in Alaux et al. (2026a) [8]

The PULSE-EU modeling approach for each CE measure is described below:

(i) **Reduction of average living area per person:** average living area per capita is a key determinant of building stock expansion. Under business-as-usual (BAU) conditions in Europe, this indicator is expected to rise due to economic and societal trends. In PULSE-EU, this parameter moderates the BAU growth trajectory by a defined percentage. For instance, if BAU projections indicate a 10% annual increase, a 1% diffusion of this measure would limit the realized increase to 9%. This measure reduces future floor area demand, thereby proportionally decreasing new construction needs, material consumption, and embodied emissions.

Table 1. Overview of assessed CE measures, their implementation levels in the building stock model and related PULSE-EU strategies.

PULSE-EU Strategies	Assessed CE measures	Implementation
Reduce per capita space demand	(i) Reduction of average living area per person	Stock-level
Prioritise better use, renovation and repair over demolition and new construction	(ii) Building service-life extension through renovation	Stock-level
	(iii) Reduction of building vacancy	Stock-level
Increase circular material use	(iv) Re-use of existing building components and materials.	Archetype-level
	(v) Increased material recycling	Archetype-level
Reduce construction and demolition waste	(vi) On-site waste sorting	Archetype-level

Adapted from Alaux et al. (2024) [6].

(ii) **Building service-life extension through renovation:** building demolition rates are modeled using probabilistic service-life distributions depending on building typologies and construction periods. This measure adjusts rates by keeping a share of buildings that would otherwise be demolished. Eligibility is limited to buildings identified for potential deep renovation (comprehensive envelope improvements and system replacements). At a 10% diffusion rate, 10% of buildings reaching end-of-life under BAU conditions are instead deep renovated and retained. This measure reduces demolition and embodied emissions from replacement construction while increasing renovation material flows and enhancing operational energy performance.

(iii) **Reduction of building vacancy:** vacancy rates are calibrated based on national statistics [14]. The vacancy reduction measure activates a share of vacant dwellings via deep renovation, shifting them to occupied status. At 10% annual diffusion, 10% of the vacant stock undergoes deep renovation each year. This offsets equivalent new construction demand, incorporating renovation material flows and embodied emissions while avoiding substantially higher emissions from new construction.

(iv) **Reuse of existing building components and materials:** material reuse substitutes a percentage of raw material inputs with recovered products, materials, or components from demolition and renovation waste streams, focusing on steel, bricks, and concrete. A 2% diffusion rate meets 2% of material demand via reuse. Reused materials carry lower environmental impacts (avoiding primary production) while accounting for recovery, processing, transport, and quality control.

(v) **Increased material recycling:** this measure is modelled through reductions in archetype-related LCA results due to increased recycled content for primary materials (steel, plastic, brick, aluminium, copper, wood, glass, concrete, insulation, gypsum). Diffusion rates represent average recycled content shares, reducing energy

demand and GHG emissions from production. Unlike (iv) reuse (direct component application), recycling involves industrial reprocessing into new products.

(vi) **On-site waste sorting:** this measure redirects a higher share of construction and demolition waste from landfill to recycling and recovery pathways. The diffusion parameter represents the percentage of waste diverted to recycling/reuse, reducing GHG emissions via lower volume sent to landfill, avoided transportation distances and raw material production. It synergizes with reuse/recycling measures by enhancing secondary material quantity and quality.

3 Results and Discussion

Collectively and under maximum diffusion, the assessed CE measures represent a total reduction of 147 $MtCO_2e$ in 2050, corresponding to an 18% decrease from 2020 levels in combined embodied and operational emissions of the EU27 building stock. The results show a sharp increase in mitigation potential through 2030, followed by a more gradual rise up to 2050. As CE measures interact dynamically, synergies arise when complementary measures show higher potential emissions once combined, for example the reinforcement of recycling through on-site waste sorting. Trade-offs also appear, such as reuse and recycling competing for the same demolition waste, or lack of timeline alignment for material loops.

Among the assessed CE measures, (i) reducing living area per capita provides the highest mitigation potential, ranking first in 22 of 27 countries and consistently within the top two overall, except in Spain, where (iii) reducing vacancy ranks first. Vacancy reduction also performs strongly, ranking second in 14 countries and within the top three in all cases. (ii) Extending building service-life through renovation achieves the third-highest potential on average, though it ranks lowest in Finland, Luxembourg, Malta, and Poland. (v) Increased material recycling and (iv) re-use of existing components follow, with recycling ranking fourth in 21 countries. (vi) On-site waste sorting shows the least impact, ranking sixth in 14 countries and fifth in the remaining 12.

Material-side measures (recycling, reuse, waste sorting) mainly target embodied emissions and have therefore relatively low individual impact compared to measures achieving greater reductions in operational emissions. However, they play an important supportive role by improving quantity and quality of secondary material flows. An observed modelling limitation for living area reduction is the neglect of potential trade-offs from additional materials required for delivering denser livable spaces. Table 2 lists the EU countries from highest to lowest absolute GHG reduction potential through the combined implementation of CE measures by 2050. These measures are individually ranked in terms of national capacities for mitigation.

Figure 1 illustrates the total potential GHG emissions reductions in 2050 from each individual CE measure assessed in the study. Emissions are expressed relative to the 2020 baseline (808 $MtCO_2e$) across the EU27. The individual results are non-additive to other measures due to synergies and trade-offs between them.

Table 2. EU countries from highest to lowest absolute GHG reduction potential (2050) along with ranked national CE measures' mitigation potential.

		CE measures								CE measures					
	EU27	1st	2nd	3rd	4th	5th	6th		EU27	1st	2nd	3rd	4th	5th	6th
1	Germany	i	ii	iii	v	vi	iv	15	Czech Rep.	i	ii	iii	v	vi	iv
2	France	i	ii	iii	v	iv	vi	16	Greece	iii	i	ii	v	iv	vi
3	Spain	iii	ii	i	v	iv	vi	17	Lithuania	iii	i	ii	v	vi	iv
4	Italy	i	iii	ii	v	iv	vi	18	Hungary	i	ii	iii	v	vi	iv
5	Belgium	i	iii	ii	v	iv	vi	19	Poland	i	iii	v	iv	vi	ii
6	Austria	i	ii	iii	v	vi	iv	20	Slovakia	i	iii	ii	v	iv	vi
7	Netherlands	i	ii	iii	v	iv	vi	21	Cyprus	i	ii	iii	v	iv	vi
8	Romania	i	iii	ii	v	iv	vi	22	Luxembourg	i	iii	v	iv	vi	ii
9	Sweden	i	ii	iii	v	vi	iv	23	Croatia	i	iii	ii	v	iv	vi
10	Finland	i	iii	v	vi	iv	ii	24	Slovenia	i	iii	ii	iv	vi	v
11	Ireland	i	iii	v	iv	ii	vi	25	Latvia	iii	i	ii	v	vi	iv
12	Portugal	i	iii	ii	v	iv	vi	26	Malta	i	iii	v	iv	vi	ii
13	Denmark	i	iii	ii	v	iv	vi	27	Estonia	i	iii	ii	v	iv	vi
14	Bulgaria	iii	i	ii	v	vi	iv								

Assessed measures are (i) average living area reduction per person, (ii) service-life extension through renovation, (iii) vacancy reduction, (iv) component/material reuse, (v) increased recycling, and (vi) on-site waste sorting.

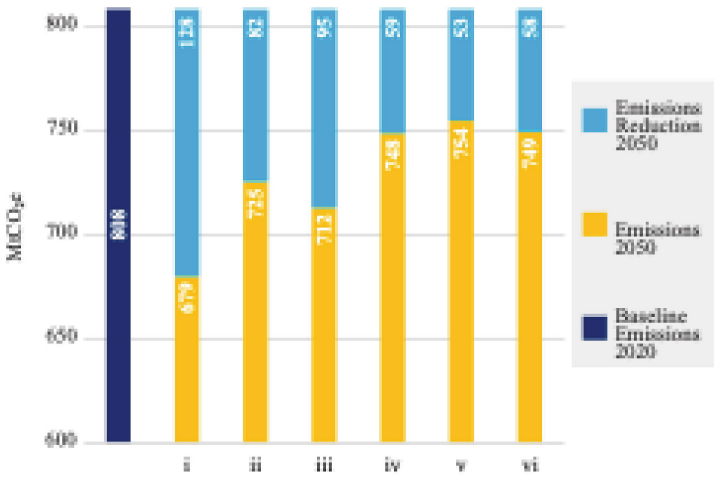


Fig. 1. Total potential GHG emissions reductions in 2050 from each individual CE measure relative to 2020 baseline emissions across the EU27.

4 Conclusion

The analysis demonstrates that CE measures offer substantial, differentiated GHG mitigation across the EU27, with a collective potential of 147 $MtCO_2e$ by 2050, equivalent to 18% of 2020 building emissions, primarily through reduced new construction and optimized material loops. Living area and vacancy reduction emerge as main levers of emission reduction, using basic economic and social factors as potentials to cut embodied emissions. However, future development of the modelling should account for possible trade-offs, such as additional materials needed to transform existing buildings into denser, livable spaces. Renovation-driven service-life extension provides consistent third-place gains despite regional differences. Material-side measures (reuse, recycling, waste sorting) contribute modestly when assessed individually, but are an important enhancer of secondary flows, underscoring the need for integrated deployment of CE measures. Further research is recommended for critical assessment of social, political and market barriers for CE measure adoption to better capture their actual implementation constraints and opportunities.

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Tailored Scenario Analysis for LCA Project Assessment in Green Public Procurement

Elisabetta Palumbo[1(✉)], Alessandra Corneli[2], Davide De Vito[1], and Alessandro Carbonari[2]

[1] Department of Engineering and Applied Sciences (DISA), University of Bergamo, Bergamo, Italy
elisabetta.palumbo@unibg.it

[2] Department of Civil and Building Engineering and Architecture (DICEA), Polytechnic University of Marche, Ancona, Italy

Abstract. Whole-building life cycle assessment (WLCA) is increasingly required by European regulations and international standards. However, the development and evaluation of alternative LCA scenarios remain complex due to the large amount of data involved, the influence of context-specific variables, and the constraints affecting design decisions. Recent developments in Green Public Procurement (GPP) introduce performance-based criteria aimed at improving the environmental quality of public works, requiring the assessment of design alternatives against a defined baseline. In this context, the production of environmental improvements becomes a critical and resource-intensive task. This paper suggests a framework for supporting the assessment of alternative LCA scenarios in public procurement processes. The approach is based on a proof-of-concept LLM-orchestrated workflow that integrates project data with external sources, such as Environmental Product Declarations (EPDs), to explore potential design improvements. The workflow is implemented through a Retrieval-Augmented Generation (RAG) architecture, enabling the semi-automated identification and evaluation of alternative materials. The method was showcased on a real case study involving a mixed-use residential building with social functions, demonstrating how the proposed approach can support the identification of lower-impact solutions and the estimation of potential environmental improvements. The results highlight the potential of LLM-orchestrated workflows to facilitate the exploration of design alternatives, while also outlining current limitations and areas for further development.

Keywords: Life Cycle Assessment (LCA) · Green Public Procurement · Environmental Product Declarations (EPD) · Artificial Intelligence · Retrieval-Augmented Generation (RAG) · Large Language Models (LLM) · Sustainability Assessment

1 Introduction

Whole Life Carbon Assessment (WLCA), which accounts for both embodied and operational greenhouse gas emissions over the entire building life cycle, is increasingly recognised as a key approach to support decarbonisation strategies in the construction

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sector. Recent European policy developments, including the revised Energy Performance of Buildings Directive (EPBD IV) [2] and the EU Taxonomy framework, emphasise the need to address both components, highlighting the growing importance of reducing embodied impacts alongside operational energy demand [3].

In this context, Life Cycle Assessment (LCA) represents the reference methodology for quantifying environmental impacts, particularly Global Warming Potential (GWP). Several European countries have already integrated LCA into their regulatory frameworks, while others are progressively introducing harmonised methodologies and reporting requirements.

In Italy, a standardised national LCA methodology is still lacking. The main reference is represented by the "Criteri Ambientali Minimi" (CAM) for buildings, developed within the Green Public Procurement (GPP) framework and mandatory for public procurement procedures [4]. The recent 2026 update introduces a simplified LCA methodology, inspired by the European Level(s) framework, focusing on selected life cycle stages and technical elements. Although simplified, this approach ensures comparability of results, which is essential in procurement processes.

Beyond methodological aspects, CAM introduce performance-based award criteria aimed at promoting environmental improvements. Within this framework, LCA is used as a comparative tool to evaluate design alternatives against a baseline scenario defined at the feasibility stage. Design proposals are required to demonstrate measurable reductions in environmental impacts, typically through material substitutions supported by Environmental Product Declarations (EPDs).

However, the development and verification of alternative LCA scenarios remain complex and resource-intensive, particularly in early design stages, where data availability is limited and uncertainty is high. This creates a significant barrier to the effective implementation of performance-based procurement criteria.

This study addresses this challenge by proposing a preliminary AI-assisted workflow to support the identification and evaluation of alternative LCA scenarios within GPP procedures. The approach integrates, into a unified workflow, tools that had previously been tested singularly, working out a Large Language Models (LLM) [5] and Retrieval-Augmented Generation (RAG) architecture [6] that matches project data with EPD databases, to enable the semi-automated exploration of lower-impact design solutions. The objective is to support designers in assessing potential improvements starting from a baseline LCA defined at the Technical-Economic Feasibility Project stage.

2 Performance-Based LCA Criteria in Italian GPP

The CAM for buildings include technical specifications, contractual clauses, and award criteria. While the first two are mandatory, award criteria apply when the Most Economically Advantageous Tender (MEAT) criterion is adopted, promoting performance beyond minimum requirements.

Within this framework, LCA is used as a comparative tool based on a baseline scenario and a set of reference indicators. The LCA report must include all mandatory indicators defined by the relevant standards, while the designer selects three key indicators for comparative assessment, including at least total GWP.

During the design phase, proposals are rewarded when they achieve a minimum improvement of 10% compared to the baseline defined at the feasibility stage. During the construction phase, alternative technical solutions proposed by contractors are evaluated against the reference design, requiring at least a 5% reduction for each selected indicator.

Such improvements are typically achieved through the substitution of building elements with alternatives of equivalent technical performance but lower environmental impact, as documented by environmental product declarations. Scoring is based both on the magnitude of the improvement and on the use of products supported by such documentation.

In this context, the verification of LCA results against the proposed improvements becomes a key element for both the evaluation and award of bids, ensuring compliance with the defined environmental performance targets.

3 Methodology

Building on the framework described above, this study explores how artificial intelligence can support the assessment of environmental improvements in public procurement processes, starting from a baseline design defined at the Technical-Economic Feasibility Project (TEFP) stage.

At this stage, the baseline LCA is typically based on generic data, due to the limited availability of product-specific EPDs. The proposed approach uses this baseline as input for an AI-assisted process aimed at identifying alternative materials characterised by lower environmental impacts and supported by EPDs, and recalculating the LCA accordingly.

The assessment considers the life cycle stages A1–A3, A4–A5, B2–B4, and C1–C4, in line with CAM requirements. The operational energy use stage (B6) is excluded, as it is not affected by material substitution.

Environmental performance is evaluated using the Global Warming Potential (GWP), expressed in $kgCO_2eq/m^2$.

3.1 Case Study and Baseline Results

The proposed approach was applied to a real case study (Fig. 1), consisting of a mixed-use residential building with social functions located in Italy, in seismic zone 3 and climatic zone D. The case study is derived from a previously developed WLC benchmark for the Italian building sector [7].

The building has two above-ground floors: the ground floor hosts a public-social facility, while the upper floor includes eight social housing units.

The structural system consists of a braced steel frame combined with reinforced concrete elements, designed to meet seismic requirements. The foundations are shallow reinforced concrete systems, and the intermediate floors are composite slabs. The main characteristics of the case study are summarised in Table 1.

The baseline LCA was developed at the TEFP stage using generic data, in line with CAM requirements. Results are expressed in terms of Global Warming Potential (GWP), in $kgCO_2eq/m^2$, considering the life cycle stages A1–A3, A4–A5, B2–B4, and C1–C4.

Table 1. Key characteristics of baseline case study

Parameter	Value
Climate zone	D
Seismic zone	3
Year of intervention	2025
Useful Floor Area (UFA)	1088.77 m^2
N° floors	2
N° apartments (N° occupants)	8 (20)
Construction type	Braced steel frame structure with reinforced concrete

The results show that the product stage (A1–A3) represents the dominant contribution, accounting for approximately 58% of the total GWP. This highlights the significant impact of material production on the overall environmental performance of the building.

The analysis by building element confirms that structural components are the main contributors to total emissions. In particular, the load-bearing structure and vertical elements account for approximately 33.9% and 25.7% of total GWP, respectively (Figs. 2 and 3).

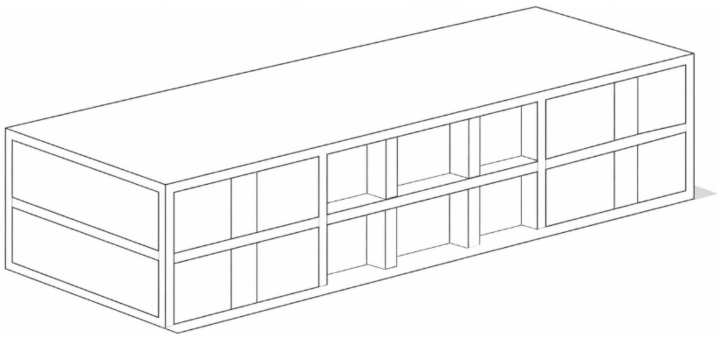


Fig. 1. Simplified archetype building geometry adopted for the study

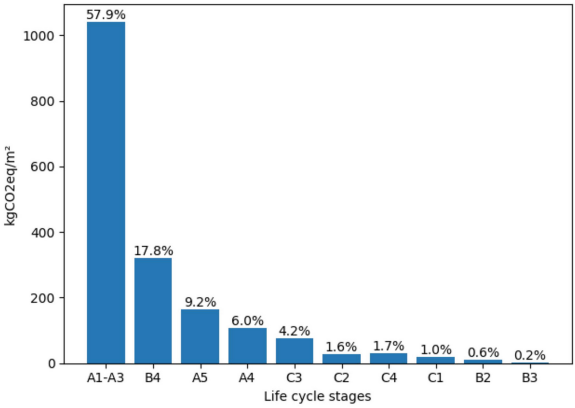


Fig. 2. Distribution of total GWP by building element across the considered life cycle stages ($kgCO_2eq/m^2$)

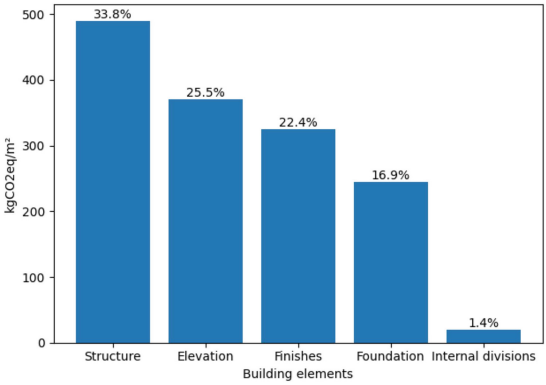


Fig. 3. Breakdown of total GWP by building element ($kgCO_2eq/m^2$ UFA)

4 LLM-Orchestrated Workflow to Assess Alternative Scenarios

4.1 Conceptual Framework

The proposed framework implements an AI-assisted workflow for the analysis and verification of CAM requirements, based on a combined LLM and RAG- based architecture (Fig. 4). The approach enables the integration of project data with external sources, such as EPD and cost databases, to support the identification of alternative design solutions.

Unlike traditional LCA workflows, which rely on manual data processing and limited datasets in early design stages, the proposed approach allows a semi-automated exploration of alternative materials starting from incomplete baseline information.

The workflow is structured into four phases: data input, AI processing, evaluation of alternatives, and decision support.

In the data input phase, project documentation (i.e. LCA reports and bill of quantities) is provided and processed to extract relevant variables for environmental assessment.

In the AI processing phase, an LLM-orchestrated system links project data with external databases, enabling data retrieval and the identification of alternative materials based on environmental and economic parameters.

The evaluation phase supports the comparison between baseline and alternative scenarios, including both environmental impacts and cost aspects.

Finally, the system generates an optimised design alternative, which is validated by the designer. The approach does not replace the design process but enhances its analytical and comparative capabilities.

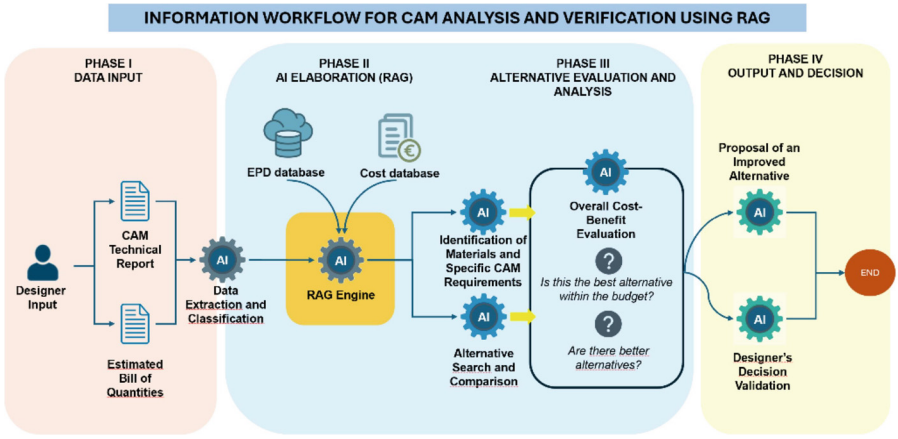


Fig. 4. Proposed RAG-based workflow for CAM analysis, alternative evaluation, and decision support.

4.2 Proof of Concept and Results

In order to preliminarily showcase the potential of the proposed framework, a proof of concept (PoC) based on LLM-orchestrated workflows was developed. The PoC performs three main tasks: (i) extraction of GWP contributions from the baseline LCA report, (ii) retrieval of LCA impact indicators from EPD documents, and (iii) estimation of the environmental impact resulting from material substitution.

The workflows are structured into three main components (Fig. 5).

The first workflow processes context-specific information from the LCA technical report to extract the breakdown of GWP contributions by building elements and life cycle stages. The second workflow retrieves GWP data from EPD documents, enabling the definition of alternative LCA scenarios. The third workflow consists of an agent that evaluates the environmental impact resulting from the replacement of materials, combining the information extracted in the previous steps.

The workflows were implemented using the open-source automation platform N8N™, a visual programming environment that enables low-code integration of components such as vector stores, embedding tools, agents, and external databases. Due to the

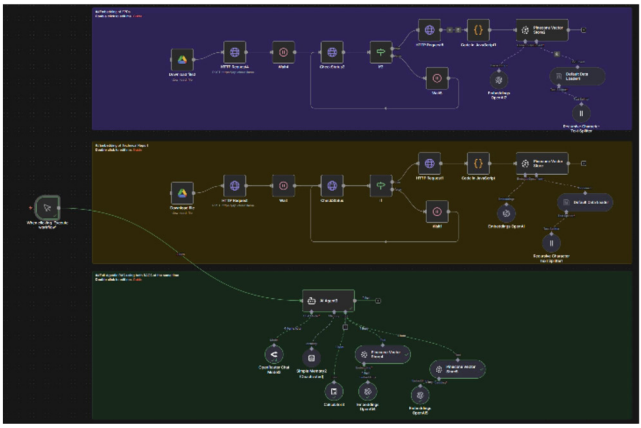


Fig. 5. LLM-orchestrated workflows to assess the GWP total figure of a building material.

heterogeneous nature of the data, a Retrieval-Augmented Generation (RAG) architecture was adopted.

The LCA technical report and the EPD datasets were embedded in a Pinecone vector store, with a chunk size of 2000 tokens and an overlap of 100, after preprocessing within LlamaIndex (v.1). This setup enabled semantic search and structured data retrieval across both contextual and technical information sources.

The analysis focused on the replacement of a concrete type used in the baseline scenario. The agent was instructed to identify the total quantity of "concrete type C35/45" from the bill of quantities, aggregating contributions from different subsystems, and to calculate the associated GWP. Subsequently, it retrieved the GWP values of an alternative concrete ("C35/45 a/c max 0.60 S5 D22.4 XC1 CAM5") from the corresponding EPD and estimated the updated environmental impact.

The results confirm the correctness of the workflow. The total quantity of concrete in the baseline scenario is 1,691,338 kg, corresponding to a GWP of 219,468.70 $kgCO_2eq$. The system calculated the GWP for the required life cycle stages, resulting in a value of 240.01 $kgCO_2eq/m^3$. Based on the alternative material, the total GWP was estimated at 169,140.85 $kgCO_2eq$.

This corresponds to a reduction of approximately 22.9% in the GWP associated with the analysed material. These results demonstrate the effectiveness of the proposed approach in supporting the quantitative assessment of alternative design solutions, enabling a structured and data-driven comparison of scenarios.

5 Conclusions

This study presents a preliminary AI-assisted approach to support the evaluation of alternative LCA scenarios within GPP procedures. Starting from a baseline LCA defined at the TEFP stage, the workflow integrates project data with external LCA datasets to identify and assess lower-impact design options.

The case study confirms that structural components are the main contributors to total GWP, highlighting them as key targets for improvement. The workflow enables the retrieval of impact data, recalculation of results, and comparison between baseline and alternative scenarios. In the analysed case, replacing a concrete type reduced the associated GWP by about 22.9%.

While promising for decision support, the approach is still limited by data availability, EPD consistency, and partial automation. Future work will expand datasets, improve environmental-economic integration, and test additional case studies.

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Tracing Resource Dependencies in Construction: Supply Chain Sufficiency as a Circularity Metric

Alejandro de Castro Mazarro(✉) and Lamiaa Ghoz

Leibniz Institute of Ecological Urban and Regional Development, Dresden, Germany
a.decastro@ioer.de

Abstract. Narrowing, slowing, and closing loops can increase the circularity of the built environment; however, they do not account for the dependence of supply chains on resource sinks from which raw construction materials are sourced. This is particularly important in the case of structural dependencies between countries for materials such as iron and wood, which are critical for urban development activities. This paper aims to conceptually address this gap by identifying supply chain sufficiency as an overlooked dimension of circularity assessment in the construction sector. To do so, we first describe existing methods that could potentially contribute to the overlooked metric, and then explore the use of the supply chain network analysis methodology in the case of iron used within Germany's construction sector to illustrate Germany's dependencies on other countries for sourcing iron and steel for construction. Our tentative results, based on 2019 international trade data, show a significant dependence of Germany on Kazakhstan and the Russian Federation for the supply of iron ore used throughout the construction supply chain for the production of construction steel. While these results still need to be depurated to incorporate domestic iron and steel production, as well as the iron intensity of construction products, they suggest the value of a potential metric that could enable countries to better assess their interdependencies regarding the production of their built environment.

Keywords: Circularity · Supply chain sufficiency · Supply chain network analysis · Material flow analysis · Construction sector · Resource dependencies

1 Introduction

To develop a circular economy for the built environment, the construction industry is currently aiming to narrow, slow, and close its resource flows. As a consequence, a number of strategies aimed at reducing waste to an ideal point of self-sustenance, from efficient material use to design for longevity, to recycling and urban mining, have gained prominence. To achieve these strategies, a large number of material circularity indicators in the built environment at micro, meso and macro levels have been created [1]. Such indicators largely focus on the efficiency of internal industrial processes, or on the productivity of materials as a share of their weight. For instance, the Material Circularity Indicator (MCI) measures how much a product's material is made from recycled

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or reused sources – in the building sector, from recovered building and infrastructure materials. Other widely accepted metrics include the Life Cycle Assessment (LCA), which quantifies the environmental impacts in terms of water, energy, or greenhouse emissions from the cradle to the grave of resource use.

Yet, as highlighted recently by the Ellen MacArthur Foundation [2], circularity is constrained by complex and globally fragmented supply chains that reduce the transparency and traceability of material flows. As circularity indicators largely focus on the reduction of waste output, a significant "blind spot" in contemporary circularity metrics lies in overlooking the primary resource sinks that commonly initiate secondary material loops in a circular system. A brief analysis of MCI may offer an insightful example of this problem. As MCI focuses on the impact of material recycling to increase circularity, it overlooks the ability for a reduction in primary resource consumption to increase the overall circularity of a supply chain. In a spatial sense, additionally, it does not distinguish whether a ton of primary raw material originates from the same country as its corresponding secondary raw material, or whether it originates from a distant region. Such bias, extended in existing circularity strategies, limits the ability to address the sufficiency of a supply chain, as well as the landscape degradation and environmental injustice derived from resource extraction in an international environmental policy context.

Construction activities, indeed, are fundamentally dependent on primary resources; recent research on the historical accumulation of anthropogenic mass demonstrates not only that the construction sector is the largest contributor to human-made mass, but also that since the "Great Acceleration" observed after 1950, the proliferation of concrete and aggregates in Europe and the United States has become the primary driver of resource extraction [3]. This "blind spot" in circularity metrics, thus, lies in overlooking the spatial politics of supply chains that, otherwise, are subject of current sustainability and spatial research [4]. The assumption that recycling can create closed domestic loops and self-sufficiency overlooks the reality that, even with a full material recycling rate, highly industrialised economies and their construction sectors substantially require the extraction of primary materials and energy from distant resource sinks, whose inflows from foreign locations are required to maintain loops [5].

The degree of sufficiency of a supply chain can be operationalised as a domestic-share metric that would measure the proportion of a resource originating within a country's own borders, compared to the total consumption of such a resource within the country. Such a metric would indicate the degree to which the supply chain is sufficient, ranging between a value of 0 (all primary resources originate abroad) to 1 (all primary resources originate domestically), according to the following formula:

Resource Sufficiency = Domestic Resource Consumption/Total Resource Consumption

We consider that "resource sufficiency" should be considered a fundamental metric of circularity integrated into the narrowing, slowing and closing of material flows within the circular economy framework. A tentative definition of resource sufficiency, in this context, would be the ability of a system to mainly rely on domestic and near resources. A sufficient supply chain would not rely on a single foreign source or primary resources, nor be dependent on risky, long-range logistics.

Given that the mapping of material flows within supply chains is a precondition for identifying sufficient supply chains, this paper follows an exploratory approach to identify existing methodologies that could map such flows. Based on this, we illustrate below the potential application of such methodologies through the brief analysis of a case study under development. Finally, the paper concludes with future research directions and limitations of this study. With these, we aim to critically evaluate current circularity metrics and identify approaches to shape a tool that explicitly incorporates supply chain dependencies into a resource sufficiency indicator.

2 Measuring Resource Sufficiency

To address the gap identified above—the absence of circularity metrics addressing supply chain dependencies—this paper explores the validity of two available methods for tracing international dependencies in supply chain networks: Material Flow Analysis (MFA) and Supply Chain Network Analysis (SCNA).

Supply chain network analysis (SCNA), used in the fields of resource security and ecosystem ecology, is a methodology that traces and measures the structural dependencies of traded products and identifies their resource origin. SCNA calculates graph traversals, namely a systematic process of algorithmic analysis exploring the relationships between nodes within a graph to extract insights. In a supply chain, Breadth-First Search (BFS) algorithms identify all Tier-1 suppliers, then all Tier-2 suppliers, gradually expanding outward to map the "breadth" of the supply network. In opposition, Depth-First Search (DFS) algorithms dive as deep as possible along a branch before backtracking. With a combination of both, SCNA can trace the journey of a material through multiple tiers of processing—for example, from a mine in Brazil to a pelletizer in the Netherlands, and a blast furnace in Germany.

An additional methodology that may assess the sufficiency of a supply chain, used within industrial ecology, is trade-linked Material flow analysis (MFA). Traditional MFA tracks the stocks and flows of materials within a defined system (like a city or a nation). Trade-linked MFA expands this by attaching "origin tags" to those flows. Trade-linked MFA incorporates material content and production yields, and at each process level, this way offering a mass-balanced account of flows - namely a closed system where the sum of inputs and outputs in the supply chain is constant.

While both types of analysis trace the location of resource flows through supply chains, they operate at different levels of analysis. Both trade-linked MFA and SCNA rely on a supply chain model that helps to structure the flows of raw and semi-finished goods in the supply chains according to trade data, namely import and export records for raw materials, semi-finished and manufactured goods. In a practical sense, they allow for mapping hidden vulnerabilities in the supply chain. They may, for example, identify deep-tier "diamond-shaped" risks, by which a diversified supply chain of semi-manufactured products relies on single raw resource sinks. These methods, also, may identify single points of failure that are invisible in traditional supply chain reporting. Additionally, they can help to identify bottlenecks for regions that are critical by their structural position in the global network. Finally, these methods help to assess the true environmental impacts of resource use. By traversing every process in the supply chain,

we can calculate the "true" carbon footprint, accounting for the energy intensity of every node from extraction to assembly. Each of these methods, however, provides a different level of consistency: SCNA can be upgraded to trade-linked MFA if it provides a mass-balanced account of material flows, for which it requires, among others, domestic production data and production yields of each process. Otherwise said, SCNA may not necessarily address the share of products distributed within each supply chain node, while the trade-linked MFA does provide such level of detail – at the expense of a higher data intensity.

3 A Case Study Snapshot: The German Construction Steel Supply Chain

To test the value of these methodologies to provide a measure of supply chain sufficiency empirically, we explore the application of a SCNA for construction steel imported in Germany in 2019—a year of significant urban development, before the global supply chain shock created by the global pandemic of 2020.

Even when in 2019, Germany was the world's 7th largest producer of pig iron, the country was heavily dependent on imported raw materials for metals and had no raw iron extracted from mines [6]. Germany's construction sector remains, in fact, a massive consumer of virgin iron and steel, as its construction industry accounts for approximately 33% of its steel consumption [7]. Iron is, on its own, the world's second most traded commodity by economic volume and a cornerstone of modern construction, with steel accounting for approximately half of all iron produced [8]. While iron mining is known to be associated with environmental catastrophes and social harms in developing regions, such as Minas Gerais and Pará in Brazil [9], these regions are decoupled from the sectors driving the demand for iron. In doing so, sectoral, national and international institutions are limited in addressing the environmental and social issues derived from mining.

To re-territorialise the iron consumed by the German construction sector into the landscapes and regions most affected by iron extraction, we present a supply chain network analysis, currently in development, from the global iron mines to the crude and conformed steel production in Europe and Germany, and to the end-use products for the construction industry in Germany. To do this, we use export data for products that are mainly used for the construction supply chain, from the UN Comtrade database according to its Harmonised System [10]. The trade data is assigned to one of the four generally agreed-upon phases: iron mining (Phase 1), iron reduction (Phase 2), steel casting (Phase 3), and production of steel goods (Phase 4). Starting with the supply chain Phase 4 and until Phase 1, we use a Breadth-First Search to find all exporting countries that have a negative weight balance with their corresponding importer countries. This means that we first analyse which countries have a negative net trade balance with Germany (namely, which countries export more steel goods than they import to Germany) (Fig. 1, right side); we then analyse which countries have a negative net trade balance with the previous exporting countries for steel casted products; and so forth for the supply chain phases 2 and 1. As products cannot travel "backwards" through the supply chain, the analysis hypothesises that all surplus weight accumulated by Germany can be found, through the supply chain, in the countries exporting iron ore.

Our model carries a number of assumptions that need to be clarified to restate its ongoing, exploratory nature. As mentioned earlier, in our analysis we have not yet assigned sector coefficients to the products of Phase 4, meaning that we carry the assumption that 100 % of the harmonized system products are used in the construction industry. On the other hand, we do not calculate the domestic production of iron ore, which limits the ability to have a mass-balanced account of resource use; this limitation, also, can be overcome in a further development of the SCNA into a full, trade-linked MFA. Last but not least, the iron/steel supply chain model can be improved to avoid data distortion from re-trade and double counting.

Our analysis revealed a high concentration of dependency in the original suppliers of iron, even when steel for construction is largely manufactured in Europe. The tentative results of our analysis, portrayed as a Sankey Diagram flow chart in Fig. 1, display the flows of iron across supply chain phases and countries, as proportional in quantity to line widths. Despite Germany's robust domestic steel industry, the diagram shows that primary iron used for construction steel was heavily reliant on two specific resource sinks: Kazakhstan and the Russian Federation, which are not the largest global iron ore producers. It should be noted that the absolute value of these flows is not as relevant as their relative value, as the values of the Sankey diagram are not mass balanced.

By mapping these flows, this paper highlights that concentrated urbanisation entails environmental and social impacts on specific extraction regions tied to construction materials, regardless of their efficient manufacturing. It also aims to address accountability gaps within the governance of trade regimes, which may foster more equitable and sustainable practices in the global iron trade. Within the context of Industrial Ecological research, the paper aims to contribute to the investigation of global resource use of cities through the identification of regional hotspots of resource extraction, which

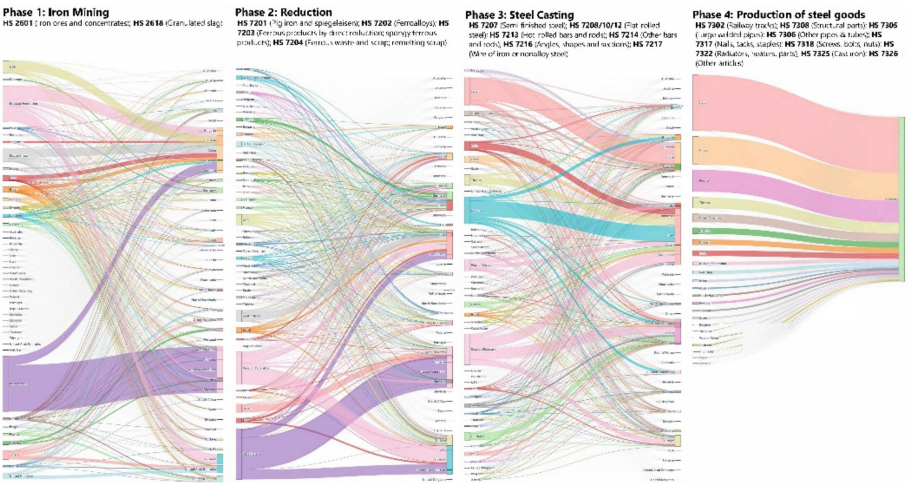


Fig. 1. Sankey diagram representing a tentative supply chain network analysis of German construction steel in 2019, across four supply chain phases: iron mining, iron reduction, steel casting, and production of steel goods.

may indicate where policy priorities need to take the lead. These results may be seen to represent a "circularity leak" by which the ability to "slow" or "narrow" loops is constrained by the external pricing and availability set by the geopolitical blocs where the steel originates.

4 Results and Recommendations

While the construction sector remains the world's largest consumer of raw materials, true circularity within cannot only be centred around the metabolisation of waste, but also around the preservation of resource sinks, which provide the materials that compose our cities. To ignore the source of primary resources implies not only a flawed imaginary of the circular economy, but also a pretext for unequal trade relations among countries to persist. We must move toward a system that is not only resource-efficient but also resource-sufficient – this means, profoundly sustainable and geopolitically secure.

Our brief analysis of Germany's iron dependencies suggests a stark geopolitical reality: the physical urban infrastructures of countries like Germany may strongly rely on the earth, mines and regions of other countries. This may serve as a cautionary for the transition of the built environment towards sufficiency: While iron may be the most visible example of these vulnerabilities, the exploration of the methods here presented for other materials involved in urbanization - like wood, copper, or rare earths - may help to describe the relative unavailability of some construction resources within some nations' borders.

If resource sufficiency could be considered a "score" to disclose in new infrastructure or building projects, then SCNA and trade-linked MFA may become potential methods to assess circularity has the potential to improve circularity reporting in the construction sector. In the context of political ecological, and postcolonial research studies, the historical tracking of sufficiency metrics may, additionally, allow to observe resource dependencies across nations over decades, and help identify unequal trade dynamics built over time.

This paper's exploratory approach provides a roadmap towards a construction sector that is just and ecological. Our approach, however, carries inherent limitations: we have reviewed existing methods but not fully tested them. Consequently, we cannot prescribe a concrete tool for integrating supply chain resilience into circularity metrics. Such methods require further validation across case studies and with robust dataset analyses. Furthermore, our empirical illustration is limited to one material (iron/steel), one country (Germany), and 1 year, which restricts generalizability. Our contribution, therefore, ends at exploration, leaving future research to empirically test our findings and develop a testable methodology.

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Circularity Indices for Buildings: A Conceptual Categorization and Comparative Analysis

Andrea Skaaland Larsen, Alvilde Bergh Wold, Rolf André Bohne, and Freja Nygaard Rasmussen(✉)

Norwegian University of Science and Technology, Trondheim, Norway
freja.n.rasmussen@ntnu.no

Abstract. Despite a widely accepted need for increased circularity in the built environment, progress is still slow. One source of confusion is the multitude of circularity indices measuring circularity performance at the building scale. Several systems exist in parallel, with profound differences in goal, scope and transparency. The aim of this article is to contribute to a more coherent and transparent knowledge base for quantifying circular resource use. The analysis includes Level(s) indicators 2.3 and 2.4, the FutureBuilt Sirkulær, DGNB Circularity Index, One Click Building Circularity tool, Madaster Circularity Indicator, the Ellen McArthur Material Circularity Indicator and the Whole Building Circularity Indicator. The work provides a structured overview of CI typologies, scope, weighting factors and levels of granularity that can support both researchers and practitioners in understanding, selecting, and combining circularity indices in the assessment of buildings. The study also identifies overlaps, gaps, and potential synergies between the indices.

Keywords: Circularity indices/indices · Building-level assessment · Material reuse · Comparative analysis · Circularity tools

1 Introduction and Theoretical Framework

The construction and real estate sector is among the most resource-intensive sectors globally, accounting for substantial material extraction, waste generation and greenhouse gas emissions. Despite growing policy and industry commitment to circular economy principles, current practice remains largely grounded in a linear extract–produce–use–dispose model. The circular economy proposes a systemic transition aimed at reducing resource extraction and environmental impacts by maintaining the value of materials, products and buildings for as long as possible while minimising waste and pollution [1].

To operationalise circular economy principles in the built environment, circularity is increasingly translated into measurable indices. An indicator represents a measurable variable describing a specific aspect of a system, whereas an index aggregates multiple indicators into a composite score. For buildings, numerous circularity assessment methods have emerged, ranging from material-based metrics such as the Material Circularity Indicator (MCI) to building-level frameworks such as Level(s). These approaches differ

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in system boundaries, data requirements, aggregation logic and weighting procedures, as well as in whether they assess current material flows or future circularity potential embedded in design strategies such as adaptability and disassembly.

As a consequence, circularity indices do not merely measure performance; they operationalise circularity through distinct methodological choices. The same building may therefore receive substantially different circularity scores depending on the selected assessment framework. This raises fundamental questions regarding comparability, transparency and the normative implications of aggregation logic within circularity metrics.

Against this background, this article addresses the following research question:

How do different circularity indices operationalise circularity in buildings, and which methodological and conceptual differences influence the assessment outcomes?

By systematically comparing selected circularity indices, the study identifies underlying assumptions, system boundaries, aggregation structures and weighting logics. In doing so, it contributes to a more transparent and critically informed understanding of circularity metrics in the built environment.

2 Methodology

This study combines a structured literature review with document analysis to identify, select, and analyse circularity indices relevant to the construction and real estate sector and to establish a systematic basis for comparison.

2.1 Circularity Indices Selection

A structured literature review was conducted to identify academic contributions on circularity indices. Snowballing of reference lists was applied to identify additional sources, and policy documents and industry frameworks were included to capture regulatory and practice-oriented perspectives beyond academic databases.

The initial pool of circularity indices was based on the review by Khadim et al. [2], supplemented by additional indices identified through the literature search. Selection was limited to indices providing quantifiable circularity assessments, i.e., those producing an overall circularity score. These scores reflect aggregated performances at building level, underpinned by embedded weightings or dynamic relationships across material, element and/or building scales. Such weighting structures and aggregation logics were given particular attention in the comparative analysis.

2.2 Comparative Analysis and Harmonisation

Each circularity index was first mapped individually according to its defined circularity concepts. Cross-cutting umbrella categories were then established to enable systematic comparison across indices with similar intent.

The indices were analysed according to their coverage of three life-cycle phases: current/pre-use, use, and future/post-use. The current/pre-use phase refers to material origin and composition prior to operation, broadly corresponding to stages A1–A5 in

CEN/TC 350 standards. The use phase captures functional performance over time, including adaptability, flexibility and durability (stage B). The future/post-use phase addresses end-of-life considerations (stage C).

In addition, the indices were mapped across three aggregation levels defined in this study: material, element and building. The material level concerns individual material inputs and their recovery potential. The element level refers to assemblies composed of multiple materials and their reuse or disassembly potential. The building level captures system-wide design attributes such as flexibility and adaptability.

Circularity concepts were consolidated into eight overarching categories to cover the range of material flows while preserving conceptual intent. A similar harmonisation was applied to circular strategies for material origin and return, resulting in four common categories: reuse, recycling, energy recovery and disposal/landfill, with qualitative distinctions such as closed- versus open-loop recycling retained where possible.

3 Results

Table 1 shows a general overview of the identified quantifiable circularity indices and their inclusion of life-cycle phases, aggregation levels and circularity concepts. The analysed tools include DGNB [3], FutureBuilt Circular (FB) [4], OneClick Building Circularity (OC) [5], Level(s) indicators L2.3 [6] and L2.4 [7], Material Circularity Indicator (MCI) [8], Madaster (Mad) [9], and the Whole-Building Circularity Indicator (WBCI) [10].

Table 1. Mapping of main circularity concepts, life-cycle phases and aggregation levels.

LC-phase	Aggregation level	Circularity concept	DGNB		FB	OC	L2.3	L2.4	MCI	Mad	WBCI
			<20a	>20a							
Pre-use	Material + Element	Material /element origin	0.45	0.60	0.60+ 0.10*	0.50			x	x	x
	Material +Element	Construction demolition waste	0.05						x	x	x
Use	Building	Flexibility / DfA	(x)				1,00				x
Post-use	Element	Detachability/ dis-sasembly element /DfD	0.10	0.05				(x)		(x)	x
	Material +Element	Material Separability	0.10	0.05				(x)			
	Material +Element	Material /element Return	0.20	0.15	0.30	0.50		1.00	x	x	x
	Material	Material compatibility	0.10	0.10							
All	Building	Aggregated calculation	(x)							x	x

*: indicates that FB splits weighting of material/ element origin into building (0.6) and backfilling (0.1).
numbers: indicate weighting factors used within each circularity index
x: marks aspects that are included in the assessment but cannot be quantified as a weighting value
(x): marks aspects that are considered as background requirements without directly influencing the score
DGNB is shown in two columns (<20a and >20a), representing buildings with a service life below and above 20 years.

3.1 Life-Cycle Phases and Aggregation Levels

As seen in Table 1, the analysed indices differ in how circularity is represented across life-cycle phases. Current/pre-use and future/post-use phases are more consistently addressed, while the use phase appears less frequently. DGNB incorporates use-phase aspects through flexibility-related criteria, though without explicit weighting. MCI and Madaster integrate the use phase indirectly through lifetime assumptions for building elements, while Level(s) indicator L2.3 emphasises adaptability at building level. In contrast, L2.4 focuses primarily on post-use recovery potential. OC concentrates largely on pre-use material assessments, whereas integrative indices such as MCI, Madaster and WBCI combine multiple life-cycle phases within a unified calculation framework.

Beyond life-cycle phases, the indices differ in their aggregation scales. Most operate primarily at material and element levels, where circularity is defined through aspects such as origin, return and separability. OC and L2.3 are particularly concentrated at these lower aggregation levels, while more comprehensive systems integrate several levels simultaneously. In DGNB, the building category is conceptually included but not explicitly weighted, which explains its marking as (x) for aggregated calculation.

WBCI stands out by explicitly introducing an intermediate system level between element and building. Circularity is calculated across material, element, system and building scales within a single aggregated equation presented by [10]

$$\mathrm{WBCI} = \frac{\mathrm{BFS}}{\mathrm{LK}} \sum \mathrm{SCI_i} * \mathrm{LK_i} \tag{1}$$

In Eq. (1) BFS denotes building-level flexibility, $\mathrm{SCI_i}$ represents the circularity score of each system derived from lower aggregation levels, and $\mathrm{LK_i}$ expresses the relative importance of each system layer, reflecting aspects such as service life and disassembly potential.

Some indices also incorporate benchmarking mechanisms. Madaster evaluates circularity relative to a reference dataset using weighted averages, enabling comparative performance assessment. In DGNB and FB, the circularity index forms part of a broader certification framework rather than functioning as a stand-alone metric.

3.2 Aggregation Logics and Circular Strategies

A central observation emerging from Table 1 is the presence of two fundamentally different aggregation logics across the analysed indices. The first group comprises DGNB, FB, OC and the Level(s) indicators L2.3 and L2.4. These systems operationalise circularity through predefined categories, typically based on mass calculations combined with explicit weighting factors. Circularity is therefore structured as a sum of weighted subscores, resulting in relatively static scoring frameworks where the relative importance of each category is predetermined.

Across the indices in this group, circularity is operationalised through strategies such as design for disassembly, adaptability, and prioritisation of material origin and return. FB, OC and DGNB rely on quantified mass-based contributions combined with explicit weighting between main and sub-categories. Within this group, DGNB applies the most differentiated weighting structure. For buildings with a service life exceeding 20 years,

DGNB and FB prioritise material or element origin in the pre-use phase over post-use return, assigning weightings of 0.6 to building material origin-related aspects. In contrast, OC distributes weight evenly between parameters, resulting in a 50/50 balance between origin-related and return-related contributions.

Level(s) differs structurally from the other indices in this group by operating as stand-alone indicators rather than a combined weighted framework. Indicator L2.3 centres on adaptability and flexibility at building level, effectively assigning full weight to design strategies within a single indicator. Indicator L2.4 treats detachability and separability primarily as enabling conditions and focuses on quantifiable post-use material return, making end-of-life recovery the dominant scored dimension.

The second group consists of MCI-based approaches, including MCI, Mad and WBCI. Rather than relying on predefined weights, these indices apply ratio-based formulas derived from the Linear Flow Index combined with lifetime or utility parameters. Material inputs, outputs and service life are integrated within a single equation, meaning that category contributions emerge dynamically from the mathematical relationships between variables rather than from externally assigned weights. Instead of allocating predefined weights to circular strategies, circularity is calculated through a composite formula in which strategic prioritisation is embedded implicitly within the mathematical structure.

Table 1 also maps the circularity concepts addressed by each indicator. Among the weighted category-based indicators, DGNB covers the broadest range of concepts, while FB and OC address a more limited subset. The MCI-based approaches incorporate several of the same concepts but to varying extents: MCI focuses primarily on material flows and lifetime, Mad expands this scope by including aspects such as detachability, and WBCI represents the broadest interpretation by also incorporating building-level strategies such as flexibility.

3.3 Material/Element Origin and Return

Material and element origin and return constitute a central dimension in several of the indices assessed in Table 1. To further clarify how circular strategies are operationalized within this dimension, Tables 2 and 3 provide a more detailed breakdown on the origin of materials and elements.

Table 2 focuses on material and element origin and illustrates the level of granularity with which the different indices differentiate between sources of material input. The aim is to show how each tool subdivides origin-related categories and how these distinctions are reflected through weighting factors where applicable. For the MCI-based approaches, such explicit category weightings are not defined. Instead, the table indicates how the variables used in the underlying formula are distributed across the mapped origin categories.

Table 2. Mapping of material/element origin across indices

			DGNB	FB	OC	MCI	Mad	WBCI
Reused/ Repurposed material		Reused	1.00	1.00	1.00	F_U	F_U	F_u
		Repurposed/remanufactured	1.00	1.00		F_U		
		Surplus from construction sites and leftover inventories		0.35				
Recycled materail		Closed loops	0.75	0.50	1.00	F_R	F_R	F_r
		Open loops	0.50					
Primary raw material / Virgin material	Renewable	Certified (high-quality, with reforestation) or comparable (rapidly renewable)** or biobased	0.75	0.00	1.00	F_S	F_{RR}	F_b **
		Primary raw material, renewable, not certified (high-quality, with reforestation) or not comparable (rapidly renewable)** or not biobased	0.50					
	Non-renewable		0.00		0.00	$\frac{V}{M}$	$\frac{V}{M}$	$\frac{V}{M'}$

As shown in Table 2, the MCI-based tools and the original MCI apply comparable categorisations of material origin. All operate with the same primary distinctions: reuse, recycled material, renewable virgin material and non-renewable virgin material. While this structure broadly reflects the waste hierarchy, it offers limited differentiation regarding qualitative material characteristics.

A methodological nuance is introduced in the 2024 update of the MCI Excel tool. Whereas earlier versions did not formally distinguish between reuse and remanufacture, the updated version specifies this distinction. However, the mathematical structure remains unchanged, as both strategies are incorporated through the same utility-related term (F_U) in the final equation. Remanufacturing is operationalised as reuse with an assumed addition of 5% virgin material input. This modification increases categorical resolution while preserving the underlying computational logic.

However, Table 2 also reveals clear differences in how virgin and renewable materials are weighted. FB assigns no positive value to virgin materials, regardless of whether they are renewable or not. OC goes one step further by awarding credit for renewable materials, but without distinguishing between certified and non-certified origin. DGNB has the most detailed approach and explicitly differentiates between certified and non-certified renewable virgin materials. Thus, not only the renewability of the material, but also documented sustainability quality is taken into account. At the same time, OC appears to be the simplest method, with default weighting given as 0 or 1, whereas DGNB and FB follow a more stepwise logic that reflects the priorities of the waste hierarchy.

The same mapping where done for material and element return. Where Table 3, representing the potential pathways for future use once materials reach the end of their service life. Similar to Table 2, the table highlights the degree of granularity across the indices, showing how return strategies are differentiated and weighted where such values are explicitly defined.

Table 3. Mapping of material/element return across indices

			DGNB	FB	OC	L2.4	MCI	Mad	WBCI
Reuse		Direct	1.00	0.67	1	1	C_U	C_U	C_u
		Preparing for reuse / remanufacture				0.9	C_U		
Recycling	High-quality closed loop recycling / Recycling pure stream		0.80	0.33	1	0.75	C_R	C_R	C_r
	Material recycling	Without effort /closed-loop with effort	0.70			0.5			
		With processing effort /open-loop recycling / mixed stream	0.60		0.5				
		Reprocessing with inferior quality / other material recycling / Recovery material	0.40			0.25			
Energy recovery	Energy recovery renewable/ biogenically certified and demonstrably low in pollutants /compost /bio decomposition		0.40	0	0.5	0.15	C_C	$\frac{W_0}{M}$	C_b
	Energy recovery non-renewable	Non-renewable/biogenic, renewable/not biogenically certified	0.20				C_E		$\frac{W_O}{M}$
		Energy disposal	0				$\frac{W_0}{M}$		
Disposal/ landfill	Disposal	Backfilling	0.20		0	0.01			
		Disposal Non-hazardous waste (LC 0-II), incl.	0.20						
		Disposal Hazardous waste (LC III-IV), disposal	0			0			

As illustrated in Table 3, the differences between the indices become more pronounced in return flows, where MCI, Mad and WBCI show greater variation in granularity at the lower levels of the waste hierarchy, i.e. energy recovery and disposal.

Table 3 further shows that DGNB stands out with the highest level of detail, operating with 11 weighting categories. The index differentiates between direct reuse and preparation for reuse, between different quality levels of recycling, as well as between different forms of energy recovery and disposal. In contrast, FB operates with only three main categories for return flows, resulting in a more aggregated assessment. OC and L2.4 lie between these extremes, with explicit weights that largely follow the ranking of the waste hierarchy.

4 Discussion

The results demonstrate substantial variation in how circularity indices define system boundaries, select reference metrics and structure aggregation. While some methods primarily quantify current material flows through mass-based balances, others emphasise future circularity potential embedded in design attributes such as adaptability and disassembly. Consequently, circularity scores are not solely reflections of material performance, but outcomes shaped by methodological design choices.

Importantly, variation occurs not only at the level of overarching assessment logic but also within comparable circularity concepts. Indices addressing material origin and return assign different weights and levels of differentiation to similar strategies. Such internal weighting structures influence how strongly recycled content, reuse potential or end-of-life scenarios contribute to the final score, thereby embedding implicit priorities within the assessment outcome.

For industry practitioners, this variation has practical consequences. When assessment outcomes depend heavily on methodological design and weighting logic, circularity becomes difficult to compare across projects and frameworks. This may create uncertainty in decision-making and benchmarking, particularly as several of these circularity indices are being integrated into policy instruments and certification schemes. Greater transparency and methodological alignment are therefore essential to ensure that circularity metrics support meaningful transformation rather than merely procedural compliance.

At the same time, the findings should be interpreted in light of certain limitations. While several widely used circularity indices were included, additional tools exist within national certification systems and emerging assessment frameworks that were not part of this study. Furthermore, the comparison primarily focuses on material input and output metrics.

5 Conclusion

This study provides a structured comparative overview of circularity index typologies, scope, weighting structures and aggregation levels, supporting researchers and practitioners in selecting and applying circularity assessment tools for buildings. The findings show that circularity indices operationalise circularity through fundamentally different methodological logics. Differences in system boundaries, reference metrics, aggregation methods and internal weighting, particularly within material origin and return, lead to divergent assessment outcomes for the same building.

Circularity indices are therefore not neutral measurements of performance, but outcomes shaped by methodological choices. This highlights the need for transparency and critical awareness when such indices are used in practice and policy. A clearer understanding of underlying assumptions is essential to ensure that circularity assessment supports consistent and meaningful transformation in the built environment.

Future research should therefore expand the scope to include additional indices, further investigate how circular design strategies and building-level performance indicators are integrated into circularity assessment, and test the indices on case studies to examine how methodological differences influence assessment outcomes.

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Exploring the Built Environment–Circular Economy–Environmental Pressure Nexus: A Bayesian Network Approach

Esma Nur Cinicioglu[1](✉), Tatjana Tambovceva[2], and Evrim Celik Madenli[3]

[1] School of Business, Istanbul University, 34320 Avcilar, Istanbul, Türkiye
esmanurc@istanbul.edu.tr
[2] Institute of Sustainable Building Materials and Engineering Systems, Riga Technical University (RTU), Riga, Latvia
[3] Department of Civil and Environmental Engineering, University of Liverpool, Liverpool, UK

Abstract. The built environment is often treated as a driver of resource depletion, waste generation, and environmental harm. Yet this view is incomplete if it overlooks that the built environment is also shaped by engineering, design, and technological choice, and may therefore function not only as a source of pressure but also as a potential site of mitigation. This study examines that tension by asking whether the built environment operates mainly as a channel through which development-related pressures intensify environmental damage, or whether its links with circularity- and efficiency-related mechanisms also reveal mitigating pathways. To address this question, the paper employs a Bayesian Network framework using Eurostat data for the 27 European Union member states over the period 2014–2023. Based on pooled country-year observations, the analysis investigates the probabilistic dependency structure among indicators representing built environment activity, circular economy processes, and environmental pressure. In doing so, it provides an integrated and interpretable view of this nexus and illustrates the value of Bayesian Networks for analyzing interdependent sustainability indicators.

Keywords: Bayesian network · Built environment · Circular economy · Environmental pressure · Sustainability

1 Introduction

The built environment is often discussed as a major driver of resource depletion, waste generation, and environmental degradation. Yet this view is incomplete if the built environment is treated as an autonomous starting point. Its expansion is shaped by broader demographic and socioeconomic pressures. Rising population, increasing density, and higher levels of economic activity create demand for housing, infrastructure, and related services, thereby stimulating construction and intensifying the use of materials, energy, and land. The built environment is therefore not simply an exogenous force acting on the environment, but also a material outcome of development pressures that influences how those pressures are translated into environmental consequences.

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Accordingly, the environmental role of the built environment depends on how development pressures are materialized through construction, design, infrastructure, and resource-use patterns. When these patterns remain linear and resource-intensive, they may aggravate environmental pollution (Liang et al., 2019), increase pressure on urban water systems (Ganguly and Cahill, 2020), and contribute to rising CO_2 emissions (Wang and Zhao, 2018). However, as a domain shaped by engineering, design, planning, and technological choices, the built environment may also support mitigation when resilience and sustainability are embedded in infrastructure design and operation. Sánchez-Silva et al. (2025) emphasize that resilience and sustainability are central to the safe and responsible evolution of the built environment, including lifelines, road networks, energy supply, and housing. This mitigation potential is reflected in energy-efficient buildings, renewable energy integration, lower material intensity, improved resource productivity, circular construction practices, and reduced water demand.

The key issue, therefore, is not whether the built environment is inherently harmful or beneficial, but how its interaction with circular economy processes and environmental outcomes can be understood within a broader system perspective. This interaction is inherently multidimensional. Environmental implications arise through construction-related waste, domestic material consumption, material footprint, greenhouse gas emissions, and water stress, while mitigation may depend on resource productivity, renewable energy use, circular material use, recycling, and recovery mechanisms. Existing studies often approach these dimensions through composite indicators, urban quality-of-life frameworks, or building-level circularity assessment tools (Psatha, 2025; Khadim et al., 2025). Although these approaches are valuable, they generally focus on aggregated scores, individual dimensions, or isolated assessment structures. They therefore provide limited insight into how built environment activity, circularity-related mechanisms, and environmental pressures interact probabilistically within a broader system.

Given this multidimensional and interdependent structure, this study employs a Bayesian Network framework to examine the built environment–circular economy–environmental pressure nexus in the European Union. The analysis is based on 18 Eurostat variables covering demographic and macroeconomic conditions, construction activity, material and waste pressures, circularity mechanisms, mitigation-related factors, and environmental outcomes. Annual observations for 27 EU countries over 2014–2023 are pooled to identify the EU-level probabilistic dependency structure among these variables, rather than to conduct a country-by-country comparison. The purpose is to investigate how built environment activity is probabilistically positioned within this system and whether it is associated mainly with environmental pressure or also with circularity- and efficiency-related mitigation pathways. The remainder of the paper presents the methodology and dataset, the learned network and analyses, and the main findings and conclusions.

2 Methodology and Data

Bayesian Networks (BNs) are directed acyclic probabilistic graphical models in which nodes represent variables and directed arcs represent probabilistic dependencies. Each node is associated with a local probability distribution, marginal if it has no parents and

conditional if it does. Under the conditional independence assumptions encoded in the graph, the joint probability distribution can be factorized into the product of these local distributions, as shown in Eq. (1)

$$P(X_1, \ldots, X_N) = \prod_{i=1}^{N} P(X_i | Pa(X_i)) \tag{1}$$

BNs are well suited to complex multivariate systems because they allow dependency structures, indirect effects, and uncertainty propagation to be examined within a unified probabilistic framework. Their data-driven and interpretable structure has supported applications in civil and reliability engineering (Wang et al., 2025; Zwirglmaier et al., 2024), risk analysis (Arabi et al., 2022), economics and finance (Cinicioglu et al., 2024), and medicine (Bhardwaj et al., 2022). They have also been used to examine broader sustainability nexuses, such as the Water–Energy–Food–Economy–Society–Environment nexus (Chai et al., 2020), and EU circular economy indicator dependencies (Cinicioglu, 2025). However, their application to the built environment–circular economy–environmental pressure nexus remains limited. The empirical dataset was obtained from the Eurostat database (European Commission, 2026) and covered the period 2014–2023. The Bayesian Network was constructed using 18 variables grouped into six analytical dimensions: contextual drivers (population density, real GDP per capita); built environment activity (construction investment, construction employment, construction GVA); resource and waste pressures (domestic material consumption, construction waste generation, municipal waste generation per capita); circularity (CDW treatment recovery rate, trade in recyclable raw materials, recycling rate of municipal waste, circular material use rate); mitigation (resource productivity, renewable energy share, energy productivity); and environmental pressure/harm (material footprint, water exploitation index, greenhouse gas emissions). These dimensions capture the broader demographic and macroeconomic context, construction-related activity, material and waste pressures, circularity mechanisms, mitigation capacity, and environmental outcomes associated with the system under study. The analysis covered the 27 EU countries for which continuous annual data were available over the full period. Each country-year was treated as one observation, yielding 270 observations per variable. The purpose was therefore not to conduct a country-by-country comparison, but to identify the EU-level probabilistic dependency structure among the selected variables and explore the relationships within the built environment–circular economy–environmental pressure nexus. The few missing observations were completed through simple within-country imputation using neighboring observations from the same country series.

Before model estimation, all variables were discretized into four ordinal states using hierarchical discretization, with thresholds determined separately for each variable according to its empirical distribution. Four states were preferred to balance interpretability and distributional differentiation. Hierarchical discretization was used because it allows state boundaries to emerge from each variable's empirical structure rather than from arbitrary cut-off values, thereby preserving variable-specific distributional characteristics. The structure of the Bayesian Network was then learned from the data using the Bayesian Search algorithm, a score-based method employing hill-climbing optimization with random restarts to identify the network structure maximizing the log-likelihood score (Bouckaert, 1995; Cooper and Herskovits, 1992). The associated

conditional probability distributions were subsequently estimated using the Expectation–Maximization (EM) algorithm, which iteratively estimates the conditional probability tables by maximizing the likelihood of the observed data given the learned network structure (Dempster et al., 1977; Lauritzen, 1995). All procedures were carried out in GeNIe 5.0 (BayesFusion, 2025).

3 Analysis and Results

Figure 1 presents the Bayesian Network obtained from the procedure described in the previous section. It represents the data-driven dependency structure of the built environment–circular economy–environmental pressure nexus. Variables are color-coded according to the six analytical dimensions to facilitate interpretation: yellow for contextual drivers, blue for built environment activity, purple for resource and waste pressures, green for circularity, orange for mitigation, and red for environmental pressure/harm. Each node displays its marginal probability distribution across the four discretized states, where $s1$ denotes the lowest value interval and $s4$ the highest. The interval labels preserve interpretability with respect to the original variable scales. The resulting network contains 44 arcs, representing direct probabilistic dependencies among the variables; however, these dependencies differ in strength.

Arc thickness in Figure 1 represents the strength of the corresponding parent–child relationship. In this study, arc strength was quantified by the average Euclidean distance between the child node's conditional probability distributions across the states of its parent. Let X and Y denote two variables in the BN, where X is the parent node and Y is the child node. For each parent state x_i, let $P(Y \mid X = x_i)$ denote the conditional probability vector of Y. The Euclidean distance between two conditional distributions of Y, corresponding to two different parent states x_i and x_j, is computed as in (2) where k denotes number of discrete states of the child variable Y. The arc strength is then obtained by averaging this distance over all pairs of parent states. Larger values indicate stronger changes in the child node's conditional distribution as the parent node moves across its states. Table 1 reports the five strongest relationships based on average arc strength.

$$d\left(x_i, x_j\right) = \sqrt{\sum_{m=1}^{k} \left[p(y_m|X = x_i) - p\left(y_m|X = x_j\right)\right]^2} \tag{2}$$

The strongest average arc strengths are observed between Material Footprint and Domestic Material Consumption (0.4964), Real GDP per capita and Domestic Material Consumption (0.4437), and Water Exploitation Index and Population Density (0.3765). These relationships indicate that the strongest probabilistic dependencies in the network are associated with broader patterns of material consumption, economic activity, and population-related pressure rather than directly with built environment activity variables. In particular, the strong dependency between Material Footprint and Domestic Material Consumption highlights the central role of consumption intensity within the nexus.

The arc structure also provides important insights into the role of built environment activity. The three built environment activity variables, namely Construction Investment, Construction Employment, and Construction Gross Value Added, do not exhibit

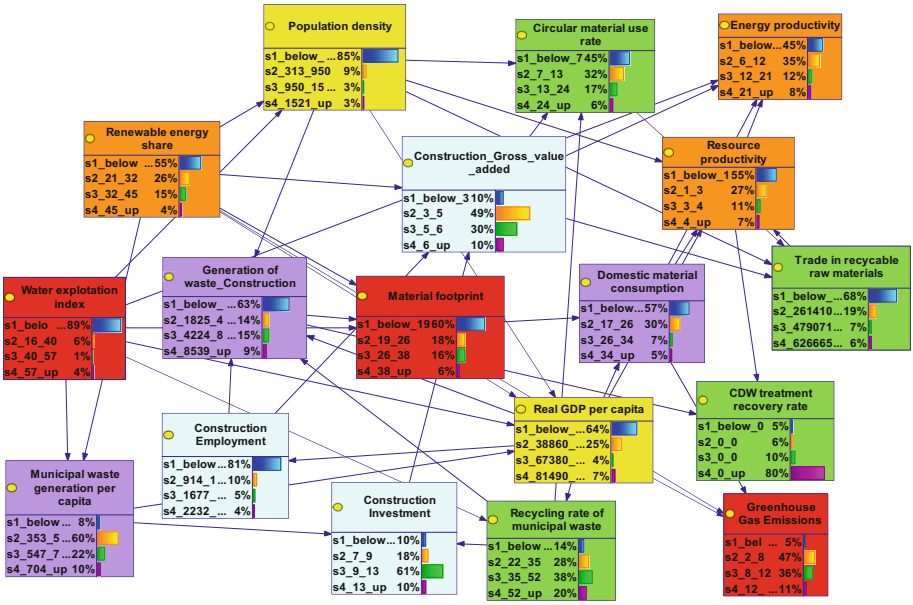


Fig. 1. Learned Bayesian Network with arc thickness indicating arc strength

Table 1. Top five parent–child relationships by average arc strength

Parent node	Child node	Average arc strength
Material footprint	Domestic material consumption	0.496399
Real GDP per capita	Domestic material consumption	0.4437
Water exploitation index	Population density	0.376494
Recycling rate of municipal waste	Construction Investment	0.350131
Renewable energy share	Municipal waste generation per capita	0.332998

direct probabilistic dependencies with the environmental pressure/harm variables. On the contrary, their direct dependencies are observed with construction-related, circularity-related, and mitigation-related variables. Construction Employment is directly connected to Construction Gross Value Added (0.2007) and Generation of Waste–Construction (0.0589). Construction Investment is directly connected to Construction Gross Value Added (0.2006), while it is also linked with Recycling Rate of Municipal Waste (0.3501) and Municipal Waste Generation per capita (0.3203). Construction Gross Value Added is directly connected to Trade in Recyclable Raw Materials (0.1344), Circular Material Use Rate (0.1167), and Energy Productivity (0.0778). This pattern is important because, rather than positioning built environment activity directly as a probabilistic driver of environmental harm, the learned network associates it with construction dynamics,

circularity-related mechanisms, and mitigation-oriented variables. The direct dependency between Construction Gross Value Added and Energy Productivity is particularly noteworthy because Energy Productivity is included as a mitigation variable. This suggests that built environment activity may also be linked to efficiency-oriented processes rather than only to resource-intensive pressures. Likewise, its direct connection with Trade in Recyclable Raw Materials may indicate that material recovery and recirculation mechanisms are becoming integrated into construction-related economic activity. Taken together, these findings support the view that the role of the built environment within the nexus is multidimensional rather than unidirectional.

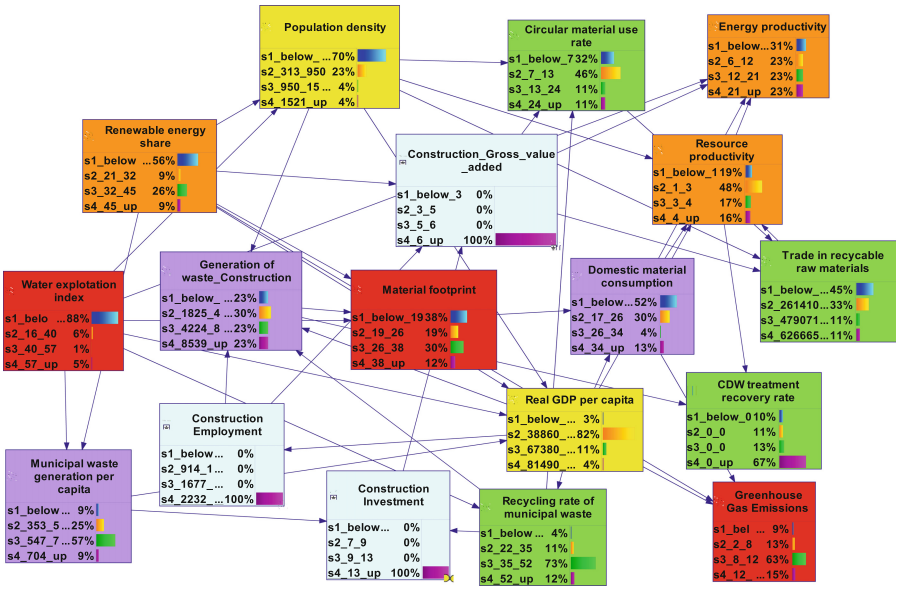


Fig. 2. Posterior probabilities of the Bayesian Network under high built environment activity, conditional on the evidence configuration Construction Gross Value Added = $s4$, Construction Investment = $s4$, and Construction Employment = $s4$

As the next step of the analysis, evidence observation was used to examine how the probability distribution of the remaining variables changes when a specific node or set of nodes is fixed to a given state. In probabilistic terms, this corresponds to conditioning the network on an entered evidence configuration, so that the posterior probability of a target variable is updated as $P(Y|E = e) = P(Y, E = e)\,/P(E = e)$. In the present analysis, the three built environment activity variables, namely Construction Gross Value Added, Construction Investment, and Construction Employment, were fixed at their highest state ($s4$). This evidence configuration is particularly informative because the learned network does not include direct arcs from built environment activity variables to the environmental pressure/harm variables. However, the absence of direct arcs does not imply that changes in the distributions of built environment activity variables are irrelevant for environmental pressure outcomes. In a Bayesian Network, probabilistic

influence may propagate through indirect paths, so conditioning one part of the network can update the posterior distributions of variables that are not directly adjacent to the evidence nodes. As shown in Fig. 2, the posterior distributions shift toward higher environmental pressure states. The most notable change is observed for Greenhouse Gas Emissions, where the probability of $s3$ increases from 36% to 63% and that of $s4$ increases from 11% to 15%. Material Footprint also shifts upward, with its distribution changing from 60%, 18%, 16%, and 6% to 38%, 19%, 30%, and 12% across states $s1$–$s4$. These findings indicate that, even in the absence of direct probabilistic dependencies, high built environment activity is still associated with stronger environmental pressure patterns through the broader dependency structure of the network, reflecting its role as an interface between socioeconomic development pressures and environmental outcomes.

4 Conclusions

The results show that the built environment cannot be interpreted as a simple direct source of environmental harm. In the learned network, built environment activity variables do not exhibit direct dependencies with environmental pressure/harm variables; instead, their direct links are mainly observed with circularity- and mitigation-related variables such as Circular Material Use Rate, Trade in Recyclable Raw Materials, Recycling Rate of Municipal Waste, and Energy Productivity. However, evidence observation indicates that high built environment activity still shifts the system toward stronger environmental pressure patterns, particularly through higher posterior probabilities for Greenhouse Gas Emissions and Material Footprint. This suggests that the built environment operates as an interface between socioeconomic development pressures and environmental outcomes, rather than as an isolated driver of harm. Overall, the findings support the need to understand the built environment–circular economy–environmental pressure nexus as a multidimensional and probabilistically interdependent system. Bayesian Networks are therefore useful for tracing both direct dependencies and indirect posterior shifts within this system.

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Climate Implications of Roof Leakages: Scenario-Based Assessment for Norwegian Buildings

Roberta Moschetti(✉), Håvard Bergsdal, Lars Gullbrekken, and Berit Time

Department of Architecture, Materials and Structures, SINTEF Community, Trondheim, Norway
roberta.moschetti@sintef.no

Abstract. Roof leakages are a frequent source of building damage, but their climate impacts remain poorly quantified. This study assesses the greenhouse gas emissions associated with representative leakage scenarios in common Norwegian roof constructions, including ventilated pitched roofs and compact flat roofs with different configurations. Three damage scenarios are analysed: (1) early detection with localised and limited damage, (2) late detection leading to moisture penetration into the insulation layer, and (3) long-term undetected leakage resulting in extensive deterioration of roof coverings and underlying components. For each scenario, the analysis includes emissions from material replacement, waste management, and energy consumption for mechanical drying. The results demonstrate a strong increase in emissions with increasing damage severity. Early detection scenarios show limited climate impact due to minor material replacement and short drying periods, whereas late detection scenarios require insulation renewal and prolonged drying, substantially increasing emissions. In the most severe long-term scenario, total emissions for a 100 m^2 compact flat roof exceed 9,000 kg CO_2-eq, driven by extensive reconstruction following prolonged moisture exposure and constrained drying conditions. To provide a broader context, the scenario-based analysis is complemented by an exploratory national-level assessment based on available statistics and building databases, showing the potential climate significance of roof leakages at the national scale. The findings highlight that proactive maintenance, timely leak identification and climate-robust roof design can significantly reduce climate impacts, underscoring the importance of preventive maintenance strategies for a resilient Norwegian building stock.

Keywords: Roof Leakage · Moisture Damage · GHG Emissions · Roof Constructions · Building Stock Resilience

1 Introduction

Worldwide, the existing building stock faces increasing risks from climate change, leading to more frequent and intense climatic events such as heavy rain, floods, frost, and heat waves. Norway is particularly exposed due to its varied climate and rugged topography,

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which create large local climatic differences and pronounced seasonal variations [1]. As a result, building envelopes in Norwegian construction must withstand demanding weather conditions, including strong winds, heavy snow loads, precipitation, freeze–thaw cycles, and large temperature variations, all of which can affect the durability and long-term performance of building components [2]. Moisture-related problems such as leaks, condensation, and water penetration can cause material deterioration, mould growth, and structural damage, often requiring resource-intensive repairs. In Norway, precipitation accounted for over 40% of building defects between 2017 and 2020. More than 70% of these defects were related to the building envelope, with most linked to roof structures [3]. Gullbrekken et al. [4] found that precipitation moisture was the primary cause in 49% of 465 pitched-roof defect cases recorded between 1993 and 2002. For compact flat roofs, precipitation or condensation of indoor moisture accounted for 73% of all defect cases [5].

Building defects can result in significant economic expenses and lead to increased greenhouse gas (GHG) emissions, thereby raising the building's overall carbon footprint [6]. Repairs or replacement of damaged components require additional extraction of materials, manufacturing, transport, and installation, all of which contribute to environmental impacts. However, quantified data on emissions associated with moisture-related damage remain limited [7]. Previous life-cycle assessment (LCA) studies have mainly focused on operational energy use and energy-related renovation, while environmental impacts of damage-related repairs have received less attention (e.g. [8]). Although some studies consider moisture safety together with the environmental performance of building envelopes [9], the climate impacts of leakage-related damage remain insufficiently quantified.

This study investigates the environmental impacts of roof-leakage-related defects in Norwegian buildings, focusing on: 1. How do leakage defects of varying severity affect typical Norwegian roof assemblies? 2. What are the associated GHG emissions from repairing such defects?

2 Methods

2.1 Roof Types and Damage Scenarios

This study explores two common roof constructions in relation to three specific damage scenarios. The analysed roof types are compact roof and ventilated roof (Figs. 1 and 2). Several alternative configurations were analysed.

Compact roofs, often referred to as warm roofs, include an insulation layer placed above the load-bearing system. The roofing layer consisted of either bitumen or PVC membrane. The 250 mm insulation layer was modelled using EPS, XPS, or mineral wool. A polyethylene vapour barrier was placed above the load-bearing structure, which varied between hollow-core concrete slabs (low-carbon), profiled steel sheets, cross-laminated timber (CLT) slabs, or timber beam systems with OSB sheathing. Ventilated roofs, also known as cold roofs, integrate an air cavity between the insulation and the roof covering. Roofing alternatives included concrete tiles, clay tiles, slate, metal sheets, and asphalt shingles. The substructure consisted of either roof decking (e.g., OSB) with a plastic wind barrier and underlay membrane, or a combined underlayment and wind barrier

solution (e.g., wood fibreboard). The insulation layer comprised 250 mm mineral wool above a polyethylene vapour barrier, with interior layers of timber battens and gypsum board.

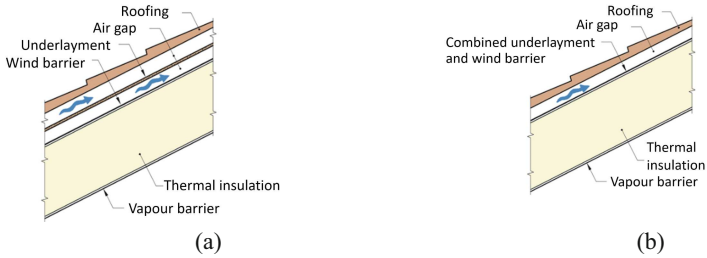


Fig. 1. Ventilated roof: (a) with separated underlayment and wind barrier; (b) combined underlayment and wind barrier. Images adapted from [10].

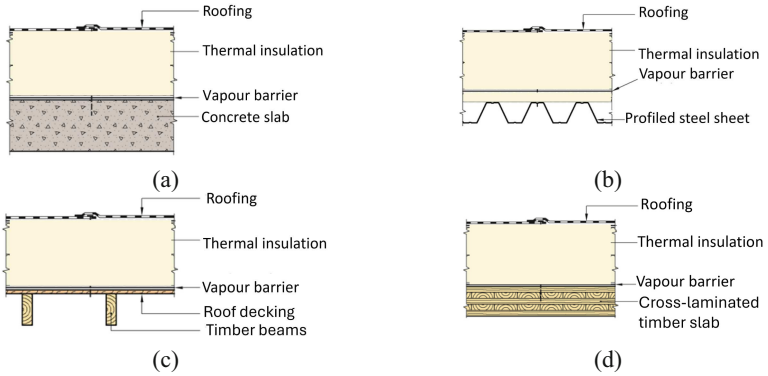


Fig. 2. Compact roof with different load-bearing structures (a. concrete slab; b. profiled steel sheet; c. timber beams; d. CLT slab. Images adapted from [11].

The three damage scenarios assessed in this study are defined as follows. Scenario 1: Minor leakage, early detection: A small perforation in the roofing layer causes localised water intrusion that does not penetrate beyond the outer membrane or significantly affect the insulation or vapour barrier. Only limited material replacement is required, corresponding to a small affected area of the roofing membrane (on the order of ~1 m^2), whereas underlying components remain unaffected. A drying period of 24 h is assumed for the locally affected roofing materials before installing the replacement membrane. This scenario applies only to compact roofs. Scenario 2: Moderate leakage, delayed detection: Water intrusion penetrates the insulation layer but does not affect the vapour barrier or primary load-bearing structure. For both ventilated and compact roofs, partial replacement of roofing and insulation layers is required, corresponding to a moderately affected area (on the order of ~10 m^2). A drying period of 14 days is assumed to dry

the affected roof materials before reconstruction. Scenario 3: Severe leakage, long-term damage: Prolonged undetected leakage causes extensive moisture damage affecting insulation, vapour barrier, and structural components. For both roof types, the entire roof area (on the order of ~100 m^2) is replaced, including roofing layers, insulation, vapour barrier, and structural elements. Structural components such as CLT slabs, timber beams, steel roof decking, and hollow-core concrete slabs are assumed to be entirely replaced due to the risk of severe moisture damage and potential corrosion. Although moisture may affect materials differently, all structural components are assumed to be replaced for consistency. This represents a conservative assumption. A 60-day drying period is applied to dry the affected building components before reconstruction.

In all scenarios, drying energy is calculated as the product of drying power (10 kW) and the scenario-specific drying duration, following [7].

2.2 GHG Emission Calculations

For each roof configuration and scenario defined in Sect. 2.1, CO_2 emissions were calculated by accounting for emissions associated with material replacement and energy consumption related to drying processes during the product stage (A1–A3). Emissions generated during the end-of-life stages (C1–C4) of the replaced materials were also included. Material-related emission factors were obtained from Environmental Product Declarations (EPDs) for representative Norwegian or Nordic building products.[1] For most materials, GWP-IOBC (Global Warming Potential – instantaneous oxidation of biogenic carbon) values reported in the EPDs were used. Energy use for drying was calculated using both Norwegian and European electricity mixes to reflect differences in carbon intensity [12]. Total emissions were calculated as shown in Eq.(1).

$$\mathrm{GHG}_{\mathrm{total}} = \sum_i \left(\mathrm{Q}_i \times \mathrm{EF}_{i,\mathrm{A1\text{--}A3}}\right) + \left(E_{\mathrm{drying}} \times \mathrm{EF}_{\mathrm{el}}\right) + \sum_j \left(\mathrm{Q}_j \times \mathrm{EF}_{j,\mathrm{C1\text{--}C4}}\right) \quad (1)$$

Where: Q_i is the quantity of new materials replacing damaged layers; $EF_{i,A1–A3}$ is the emission factor for product stage (A1–A3); E_{drying} is the electricity consumption for drying (operating hours × dehumidifier power); EF_{el} is the emission factor of the electricity mix; Q_j is the quantity of materials removed and sent to waste treatment; $EF_{j,C1–C4}$ is the emission factor for end-of-life stages (C1–C4).

[1] 1. Concrete roof tiles. Benders Sverige AB. 2. Clay roofing tiles and fittings. BMI Sverige AB. 3. Natural slate stone, natural surface with hand-cut or sawn edge. Oppdal Minera Skifer AS. 4. Construction organic coated low profiles. ArcelorMittal Construction Norge AS. 5. Isola Roof Shingle Premium Pitched. Isola AS. 6. Bitumen roofing shingles. BMI Finland. 7 Planed softwood timber (pine or spruce). Byglandsfjord Sagbruk AS. 8. Roof underlay board. Hunton Fiber AS. 9. Particleboard ekstra. Forestia AS. 10. Isokraft Xtreme. Isola AS. 11. Tyvek Soft Xtra. Isola AS. 12. Glava Proff 34 Plate. Glava AS. 13. KullafolieT M 0,15 mm. Kullaplast. 14. Gyproc Normal climate standard plasterboard. Saint-Gobain Byggevarer AS. 15. Isola Mestertekk. Isola AS. 16. Protan SE 1.6 Roofing Membrane. Protan AS. 17. EPS Insulation boards. Bewi ASA. 18. Jackofoam XPS. Bewi ASA. 19. ROCKWOOL® stone wool thermal insulation. Rockwool Norden. 20. Hot-Dip Galvanised Building Products. Ruukki Construction Oy. 21. Hollow-core slab. Spenncon AS. 22. Cross-laminated timber. Splitkon AS. 23. Particleboard standard. Forestia AS 24. Spruce glulam. Moelven AS.

2.3 National Level Assessment

A simplified assessment was conducted to analyse the potential effect of roof damages on national-level GHG emissions. The aim was to present a possible order of magnitude rather than precise estimates. National statistics on the number of dwellings by age cohort and dwelling type (detached, semi-detached, terraced, multi-apartment and co-housing) were used to estimate the total number of buildings. A simplified classification of roof types across building types and age cohorts was then applied to estimate the distribution between ventilated and compact roofs, resulting in an approximate split of 78% ventilated and 22% compact constructions. However, compact roofs are more prevalent in building types with a larger roof area. Crude estimates for roof area at the national building stock level indicate a roughly equal distribution between the two types.

Emissions were estimated per building based on the three scenarios described earlier, representing repair or replacement of approximately 1 m^2, 10 m^2 and 100 m^2 of roof area. Total emissions were calculated by multiplying the number of buildings in each roof category by the emission factor associated with the respective scenario. A conservative approach is applied by selecting the highest emission factor for each of the three assessed scenarios and roof type. Three shares of the building stock (1%, 5%, and 10%) were assumed to experience roof damage, as no empirical data were available for this parameter. Damage extent followed the three scenarios, assuming uniform damage magnitude within each scenario.

3 Results and Discussion

This section presents the life-cycle GHG emissions of the analysed roof configurations across three damage scenarios, expressed per square metre of affected roof area for comparison. Within each scenario, material-related emissions may be assumed to scale linearly with the affected roof area when extrapolating results to other damage extents. In contrast, drying energy does not necessarily scale proportionally with area, as it depends on drying duration and practical constraints such as equipment capacity.

Scenario 1 considers compact roofs only. Total emissions are relatively low (approximately 7–12 kg CO_2-eq), with plastic membranes showing higher impacts than bitumen membranes. For bitumen membranes, emissions are mainly driven by the product stage and drying energy use, whereas end-of-life stages contribute only a minor share. For plastic membranes, the product stage, end-of-life stages, and energy use all contribute substantially.

Figures 3 and 4 present results for Scenario 2, where both compact and ventilated pitched roofs are considered. Emissions increase compared to Scenario 1 due to larger replacement areas, ranging from about 21 to 57 kg CO_2-eq/m^2, depending on roof configuration. The product stage dominates the life-cycle impact, while drying energy contributes with a smaller share. Differences between compact and ventilated roofs are generally moderate, with the relative ranking depending on the materials included in each configuration. For compact roofs, XPS insulation with plastic membranes causes more emissions, while mineral wool with bitumen membranes results in lower impacts. For ventilated roofs, emissions mainly depend on the roof covering, with concrete tiles showing the lowest values.

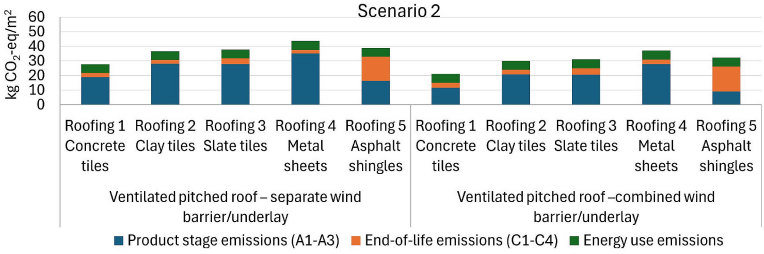


Fig. 3. Life-cycle GHG emissions for ventilated roofs under Scenario 2, expressed per m^2 (based on an affected area of 10 m^2).

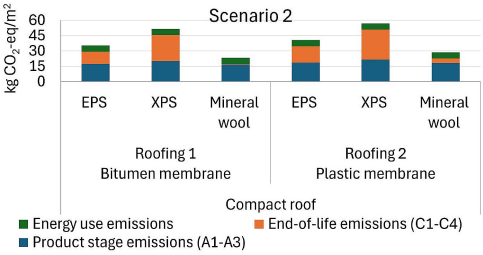


Fig. 4. Life-cycle GHG emissions for compact roofs under Scenario 2, expressed per m^2 (based on an affected area of 10 m^2).

Figures 5 and 6 show results for Scenario 3, considering both compact and ventilated pitched roofs. Emissions increase substantially compared to Scenario 2, reaching approximately 20 to 95 kg CO_2-eq/m^2 depending on the roof configuration.

Differences between compact and ventilated roofs become more pronounced, with the highest values observed for compact roof configurations combining XPS insulation and plastic membranes. The product stage generally represents the dominant contributor to total impacts. Overall, insulation type and membrane choice significantly influence results, with XPS insulation and plastic membranes consistently leading to higher impacts than EPS, mineral wool, or bitumen alternatives.

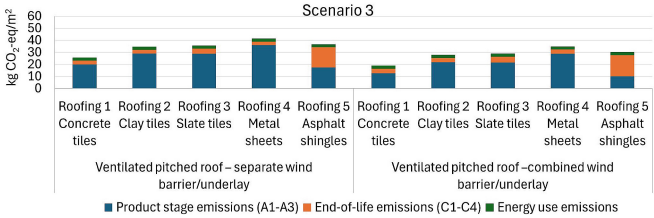


Fig. 5. Life-cycle GHG emissions for ventilated pitched roofs under Scenario 3, expressed per m^2 (based on an affected area of 100 m^2).

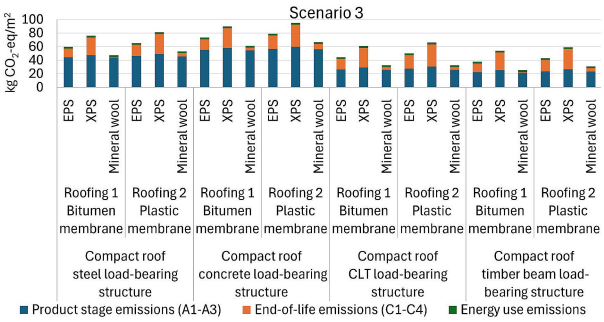


Fig. 6. Life-cycle GHG emissions for compact roofs under Scenario 3, expressed per m^2 (based on an affected area of 100 m^2).

In the graphs of Figs. 3–6, emissions from energy use are calculated with the Norwegian electricity mix (0.018 kg CO_2-eq/kWh). Using the EU electricity mix (0.136 kg CO_2-eq/kWh) rather than the Norwegian mix would substantially increase drying-related emissions across all scenarios, particularly for those requiring longer drying periods.

The results of the national-level GHG assessment are presented in Table 1. Estimated emissions show a wide range of outcomes, ranging from 72 t CO_2-eq for the lowest share of affected buildings and smallest damage scenario to 0.9 Mt. CO_2-eq for the worst-case scenario. Although emissions per damage event are lower for ventilated roofs, their contribution to total emissions is higher since more than three-quarters of buildings are estimated to have this roof type.

Table 1 Estimated national GHG emissions from roof damage by scenario and share of affected buildings. Scenario 1 applies only to compact roofs.

Share of affected buildings	t CO_2-eq					
	Scenario 1 (small damage)		Scenario 2 (medium damage)		Scenario 3 (large damage)	
	Ventilated roof	Compact roof	Ventilated roof	Compact roof	Ventilated roof	Compact roof
1%	–	72	9,200	3,300	87,470	54,940
5%	–	359	46,000	16,470	437,370	274,720
10%	–	719	92,000	32,950	874,740	549,440

4 Conclusions

This study evaluates greenhouse gas (GHG) emissions from leakage scenarios in typical Norwegian roofs, including ventilated pitched and compact flat roofs with various structures. Three scenarios are considered: (1) early detection with minor damage, (2)

delayed detection with insulation affected, and (3) long-term unnoticed leakage causing major deterioration. Emissions from material replacement, waste, and drying are analysed. As expected, emissions increase with damage severity; early detection results in low impacts, while long-term leakage exceeds 9,000 kg CO_2-eq for a 100 m^2 flat roof. At the national level, estimated emissions vary widely depending on the share of affected buildings and the damage scenario, ranging from tens of tonnes to nearly 1 Mt. CO_2-eq in worst-case scenarios (approximately equivalent to the annual emissions of 140,000 Norwegians). These findings highlight the importance of early leak detection and maintenance to reduce repair needs and associated emissions. Limitations of this study should be acknowledged. The scenarios are based on simplified assumptions about the extent of damage, repair needs, and drying periods, which may vary in practice. The results also rely on emission factors from Environmental Product Declarations (EPDs), which may rely on varying assumptions, particularly for end-of-life stages. Building- and national-level estimates are therefore indicative. Future research should incorporate empirical damage data and more detailed modelling of moisture development, repair strategies, and related emissions.

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Life Cycle Assessment of Icelandic Volcanic Pozzolans as Low-Carbon Supplementary Cementitious Materials

Mohammed Hamdallah[1(✉)], Diego Costa[2], Jukka Heinonen[1], and David Christian Finger[2]

[1] Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavík, Iceland
mah118@hi.is

[2] Department of Engineering, Reykjavik University, Reykjavík, Iceland

Abstract. The cement industry is a major contributor to global greenhouse gas emissions, predominantly due to clinker production. Supplementary Cementitious Materials (SCMs) represent an effective mitigation strategy, yet conventional SCMs such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are becoming increasingly scarce. Volcanic pozzolans offer a promising natural alternative, and Iceland possesses extensive deposits that have not yet been evaluated from an environmental perspective. This study presents the first cradle-to-gate Life Cycle Assessment (LCA) of Icelandic Volcanic Pozzolan (VPI) production, drawing on primary data from three extraction sites and a planned processing facility in Þorlákshöfn—Lambafell, Litla Sandfell, and Landeyjahöfn—and secondary data from GaBi and Ecoinvent. A declared unit of one tonne of VPI is assessed across all ReCiPe 2016 midpoint impact categories. Results show that VPI's climate change impact of 25.5 kg CO_2-eq/t falls between FA (3–10 kg CO_2-eq/t) and GGBFS (50–80 kg CO_2-eq/t), confirming its competitiveness with established SCMs while offering the strategic advantage of abundant local supply. Marine dredging operations emerge as the dominant environmental hotspot, accounting for approximately 48.1% of total CO_2-equivalent emissions. The findings confirm VPI as a robustly low-carbon SCM and support its large-scale adoption in sustainable cement production.

Keywords: Life Cycle Assessment · Supplementary Cementitious Materials · Icelandic Volcanic Pozzolan · Low-Carbon Cement

1 Introduction

The cement industry accounts for nearly 8% of global anthropogenic CO_2 emissions, driven primarily by clinker production, while concrete is the second most consumed material worldwide after water. It simultaneously faces accelerated deterioration under changing climatic conditions [1, 2]. This creates a self-reinforcing cycle: greater emissions from cement production intensify climate change, which accelerates concrete degradation and increases demand for new construction. At the regional scale, concrete represents approximately 70% of the Icelandic building stock [3], underscoring the urgency of sustainable production strategies in this context.

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Partially substituting clinker with Supplementary Cementitious Materials (SCMs) is a widely accepted decarbonization pathway [4]. Industrial by-products such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are the most established SCMs, with substitution levels reaching up to 40% [5]. However, their dwindling availability has driven growing interest in natural pozzolans—siliceous or aluminosilicate materials of volcanic origin that react chemically with calcium hydroxide to form cementitious compounds [6]. In the Nordic context, Adediran et al. [7] identified Icelandic volcanic pozzolans (VPI) as a promising and abundant SCM candidate, subsequently confirmed in a comparative evaluation of 15 SCMs in which VPI ranked as high-performing owing to its elevated reactivity and highly amorphous microstructure [7].

Life Cycle Assessment (LCA) is the most comprehensive methodology for evaluating SCM environmental performance across multiple impact categories [8]. The growing literature on volcanic pozzolans consistently demonstrates their technical viability while revealing a critical gap: no study has yet conducted a multi-impact-category LCA of volcanic pozzolans sourced from geographically distinct extraction sites. Existing assessments have been largely limited to global warming potential, neglecting acidification, eutrophication, and resource depletion. The influence of extraction location on environmental profile also remains entirely unexamined, despite the well-documented mineralogical variability of Icelandic volcanic deposits.

To address these gaps, this study conducts a process-based LCA of VPI from three distinct Icelandic sites, with site-specific inventory data. The study aims to: (1) quantify the environmental impacts of VPI production and VPI-blended cement across multiple categories relative to OPC; (2) evaluate the influence of extraction site on environmental performance; and (3) identify, through contribution analysis, the key hotspots driving environmental burdens.

2 Methodology

This study employs process-type LCA (PLCA), following the ISO 14040/14044 framework, encompassing four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [9].

2.1 Case Study Description

VPI material is extracted from three sites in southern Iceland (Fig. 1): (i) Lambafell (LF), an active quarry transitioning to VPI extraction with an annual capacity of approximately 541,390 t; (ii) Litla Sandfell (LS), a newly identified deposit projected to yield 1.0 Mt./year; and (iii) Landeyjahöfn (LH), an offshore marine sediment site also anticipated to yield approximately 1.0 Mt./year. Centralized processing is conducted at a proposed facility in Þorlákshöfn (TPH). The production mix corresponds to 10% from LF, 23% from LS, and 67% from LH per tonne of VPI. Processing includes freshwater washing of LH material (chloride reduction to <0.1%), sequential ball milling to below 10 μm, and waste-heat-integrated drying.

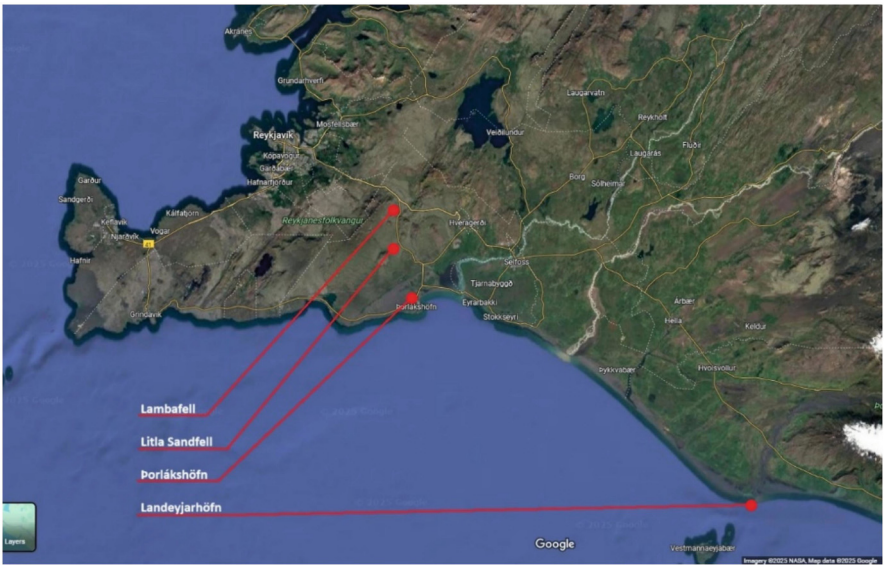


Fig. 1. Geographical distribution of VPI extraction sites and the Þorlákshöfn processing facility.

2.2 Goal, Scope, and Declared Units

The declared unit is one tonne of VPI (cradle-to-gate). System boundaries follow EN 15804 modules A1–A3: raw material extraction (A1), transport to TPH (A2), and centralized processing including washing, grinding, and drying (A3). Where co-products arise, specifically the aggregate by-product at LF (34% by mass) and LS (10% by mass), environmental burdens are allocated on a mass basis in accordance with the ISO 14044 physical allocation hierarchy. This approach is considered appropriate given that VPI constitutes the dominant mass fraction at both sites (66% and 90%, respectively), and that LH, contributing 67% of the total production mix, yields no by-product, rendering allocation irrelevant for the majority of system inputs. Moisture content was assumed to be 30% for LB and LS, and 50% for LH.

2.3 Life Cycle Inventory

Primary inventory data were collected between September 2023 and April 2024 from engineers and project managers at BM Vallá, Hornsteinn, and Heidelberg Materials. LF provided detailed operational data as the only active site; LS and TPH inventories were estimated from anticipated operational parameters. Secondary data were sourced from GaBi (v8.0) and Ecoinvent. Key inventory parameters are summarised in Table 1. The complete process-level inventory, including energy inputs per unit process, is provided as supplementary material at: LCA for the VPI Material.mmap

The mass flow of different processes on the GaBi model is shown on Fig. 2.

Table 1. Key life cycle inventory parameters per production site.

Parameter	LF	LS	TPH (incl. LH)
Material mined (t/yr)	541,390	1,000,000	1,000,000
Diesel (L/yr)	621,308	1,185,000	2,575,000
Electricity (kWh/yr)	–	3,600,000	410,000,000
Water (m^3/yr)	–	–	1,000,000

2.4 Life Cycle Impact Assessment (LCIA)

Environmental impacts were characterised using the ReCiPe 2016 Midpoint (H) method, implemented in GaBi 8.0, covering 10 midpoint impact categories. Results are further interpreted through Environmental Footprint (EF 3.1) normalisation to enable cross-category comparison [10].

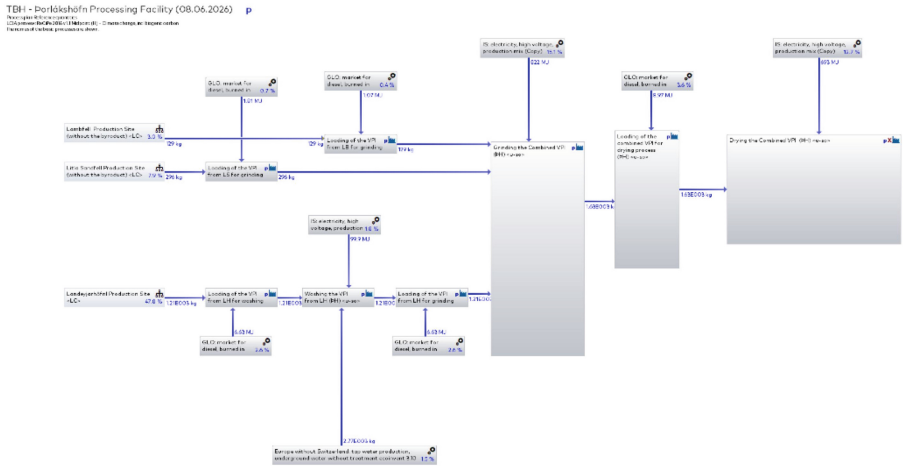


Fig. 2. Mass flow of Production Processes of the VPI Material – GaBi Model.

3 Results

3.1 LCIA Results

The LCIA results are presented in Table 2. The climate change impact of VPI production is 25.5 kg CO_2-eq per tonne of Icelandic Volcanic Pozzolan (VPI) produced. For context, OPC production typically generates 750–900 kg CO_2-eq/t [11], meaning VPI carries approximately 97% lower climate change impact per tonne of material. At an 18% clinker substitution rate, incorporating VPI reduces the carbon intensity of blended

cement from approximately 820 kg CO_2-eq/t (OPC) to approximately 698 kg CO_2-eq/t—a reduction of approximately 15% per tonne of cement binder. Other notable impact categories include Terrestrial Acidification (0.097 kg SO_2-eq), Fossil Resource Depletion (6.79 kg oil-eq), and Land Use (0.235 annual crop eq·yr), all substantially lower than OPC benchmarks.

Table 2. Cradle-to-gate LCIA results (per 1 t of VPI, ReCiPe 2016 Midpoint H).

Impact Category	Value	Unit
Climate Change	2.55E+01	kg CO_2-eq
Stratospheric Ozone Depletion	8.45E−06	kg CFC-11 eq
Photochemical Ozone Formation	1.99E−01	kg NO_n eq
Fine Particulate Matter Formation	4.89E−02	kg PM2.5 eq
Terrestrial Acidification	9.70E−02	kg SO_2 eq
Freshwater Eutrophication	2.38E−03	kg P eq
Marine Eutrophication	3.49E−04	kg N eq
Freshwater Ecotoxicity	1.95E−01	kg 1,4-DCB eq
Fossil Resource Depletion	6.79E+00	kg oil eq
Land Use	2.35E−01	annual crop eq·yr

3.2 Contribution (Hotspot) Analysis

The site-level contribution analysis reveals that LH dominates the climate change impact, accounting for 48.1% of total emissions, attributed entirely to marine dredging, the 70 km sailing distance, and onshore pumping operations. The terrestrial sites contribute comparatively little: LF accounts for 3.1%, of which 71% arises from truck transport to TPH, while LS contributes 8.0%, with 58.6% attributable to its high emissions factor despite the proximity to TPH site (22 km for LF and 16 km for LS). At the process level, grinding (14.19%), drying (12.6%), and diesel-powered loading operations (14.15%) are the next most significant contributors, with washing accounting for a further 2.1%. Together, these findings confirm that the environmental profile of the system is predominantly shaped by the energy and logistics intensity of the LH marine extraction stage rather than by the processing operations at TPH, which benefit substantially from Iceland's near-zero-carbon renewable electricity grid. The site- and process-level contributions are illustrated in Figs. 3 and 4, respectively.

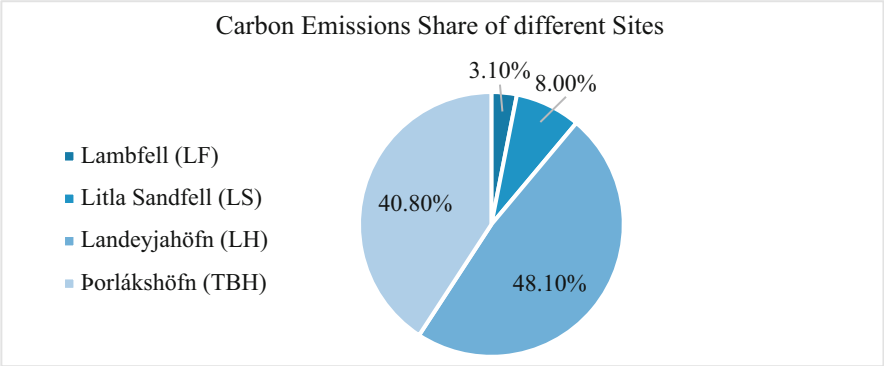


Fig. 3. Site-level contribution to the Climate Change impact category per tonne of VPI produced.

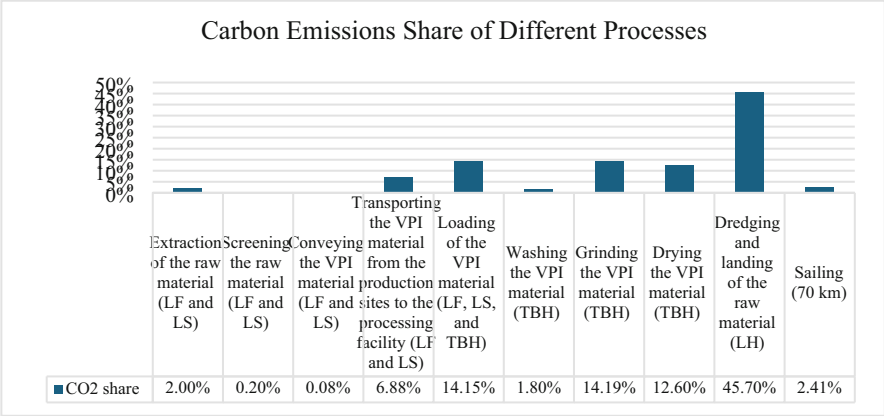


Fig. 4. Process-level contribution to the Climate Change impact category per tonne of VPI produced.

4 Discussion

This study presents the first publicly available, multi-impact-category process LCA of Icelandic volcanic pozzolans, benchmarked across three geographically distinct extraction sites. The result of 25.5 kg CO_2-eq/t reflects the advantageous combination of Iceland's renewable electricity grid and a fully domestic supply chain, firmly establishing VPI as a low-carbon competitive SCM. These findings directly respond to the research gap identified by Liu et al. [12] and Adediran et al. [7], who established the technical merit of volcanic pozzolans in the Nordic context while calling for rigorous environmental assessment. The result also highlights the significant environmental benefit of processing VPI domestically in Iceland compared to exporting raw material for

processing abroad, where fossil fuel-based energy sources and international shipping would substantially increase the overall climate change impact.

Compared to conventional SCMs, VPI is highly competitive. FA typically generates 3–10 kg CO_2-eq/t and GGBFS around 50–80 kg CO_2-eq/t when accounting for full processing impacts, meaning VPI's climate change impact of 25.5 kg CO_2-eq/t falls between these two established alternatives. However, both FA and GGBFS are industrial by-products with limited and declining availability. VPI, by contrast, is an abundant primary resource in Iceland with multi-million-tonne extraction potential, making it a strategically robust alternative independent of industrial supply chains. Importantly, the present study demonstrates that this climate advantage extends to other impact categories—including acidification, eutrophication, and resource depletion—providing a more complete environmental justification for VPI adoption than previously available. The VPI result is also notably lower than the 60 kg CO_2-eq/t reported for volcanic ash sourced from Indonesia and processed for use in Hong Kong by Hossain et al. [13], a difference attributable to Iceland's near-zero-carbon electricity grid and the absence of international shipping in the present system boundary—both structural advantages of domestic Icelandic production that further strengthen the environmental case for VPI.

The dominance of LH marine dredging (48.1% of total climate change impact) is the most actionable finding of this study. It indicates that the overall environmental performance of the system is highly sensitive to the share of LH-sourced material in the production mix and the transportation distance to TPH, which explains the low emissions of LF and LS for their proximity to TPH. Increasing the proportion of terrestrial feedstock from LF and LS, or improving vessel fuel efficiency, would yield the greatest environmental gains. This finding should directly inform production strategy decisions by Heidelberg Materials and associated stakeholders.

Several limitations should be noted. First, inventory data for LS and TPH are based on anticipated rather than measured operational parameters, introducing uncertainty in those estimates. Second, the cradle-to-gate boundary excludes use-phase benefits; a full cradle-to-grave analysis incorporating VPI's service life extension effects would likely strengthen the environmental case further. Third, a formal uncertainty and scenario analysis is planned for the journal version of this work to quantify result variability across all impact categories.

5 Conclusions

This study presents the first publicly available, multi-impact-category process LCA of Icelandic volcanic pozzolans. The principal findings are as follows:

1) VPI production generates 25.5 kg CO_2-eq per tonne (cradle-to-gate), representing approximately 97% lower climate change impact than OPC (750–900 kg CO_2-eq/t), firmly establishing VPI as a low-carbon SCM.
2) VPI carries 49–68% lower climate change impact than GGBFS (50–80 kg CO_2-eq/t), making it highly competitive with the most widely used industrial SCM.
3) VPI's climate change impact is higher than FA (3–10 kg CO_2-eq/t); however, FA is an industrial by-product with declining availability, whereas VPI is an abundant primary resource with multi-million-tonne extraction potential in Iceland.

4) Marine dredging at the LH site accounts for 48.1% of total climate change impact, confirming it as the dominant environmental hotspot and the primary lever for mitigation through production mix optimisation.
5) Grinding (14.19%) and drying (12.6%) are the next largest contributors, reflecting the energy intensity of fine comminution—substantially mitigated by Iceland's near-zero-carbon renewable electricity grid.
6) Domestic processing in Iceland using renewable energy offers a substantial environmental advantage over exporting raw material for processing abroad using fossil fuel-based energy, where international shipping and oil-based drying would increase the climate change impact by an order of magnitude.
7) At an 18% clinker substitution rate, VPI-blended cement carries approximately 15% lower climate change impact than OPC, from ~820 kg CO_2-eq/t to ~698 kg CO_2-eq/t, given VPI's near-negligible carbon footprint of 25.5 kg CO_2-eq/t relative to clinker.

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From Mineral Wool to Hemp: Quantification of the Environmental Impact of Roofs in Modern Timber Buildings

Silvia Vilčeková[1], Jana Budajová[2(✉)], Eva Krídlová Burdová[1], and Katarína Harčárová[1]

[1] Institute for Sustainable and Circular Construction, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 042 00 Košice, Slovakia
[2] Expert's Institute in Construction, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 042 00 Košice, Slovakia
jana.budajova@tuke.sk

Abstract. This paper presents a comparative life cycle assessment (LCA) of five construction variants of wooden flat roofs with the aim of evaluating their environmental impact depending on the thermal insulation used. The assessment focuses on conventional materials such as mineral wool in direct comparison with ecological alternatives in the form of cellulose, sheep's wool, linen and hemp insulation. The main indicator monitored is global warming potential (GWP), with the results pointing to significant differences in biogenic carbon, where natural insulations benefit from their ability to sequester CO_2. The study provides relevant data for optimizing the design of wooden buildings in the context of reducing the carbon footprint and transitioning to a circular economy in construction.

Keywords: Life Cycle Assessment · Wooden Flat Roof · Global Warming Potential · Carbon Footprint

1 Introduction

The construction sector urgently needs to reduce greenhouse gas emissions contributing to global warming [1]. In the context of European climate targets, attention is shifting from operational energy to minimizing embodied carbon in building materials [2]. Conventional insulation materials like mineral wool, despite excellent thermal properties, require high energy consumption during production [3]. Conversely, natural materials reduce the carbon footprint by storing atmospheric carbon through photosynthesis, creating temporary carbon storage within the structure [4]. Beyond insulation, roof cladding is crucial for climate change adaptation [5], with green roofs increasingly used to mitigate the urban heat island effect and improve rainwater management [6]. Although LCA analyses can show higher operational impacts for green roofs due to maintenance and water use, their long-term ecosystem services such as evapotranspiration and thermal stabilization are often not fully captured by standard GWP indicators [7, 8]. This

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study presents a comprehensive LCA comparison of five wooden flat roof structures, combining conventional mineral wool with natural alternatives (hemp, cellulose, linen, sheep's wool) across three vegetation and two gravel variants. The aim is to evaluate their GWP impacts and identify the most environmentally optimal solution for sustainable construction.

2 Materials and Methods

The study analyzes five variants of wooden flat roof structures with an emphasis on comparing conventional and natural insulation materials. The life cycle of these structures was assessed using the LCA method. This complex method enables systematic collection and analysis of data on inputs, outputs, and environmental impacts of individual components throughout the entire life cycle of the composition.

2.1 Goal and Scope

The main goal was to compare the environmental impact of five proposed roof composition variants (R1 – mineral wool, R2 – hemp, R3 – sheep's wool, R4 – cellulose, R5 – linen). The service life of the structures was estimated at 50 years, which is the standard period for LCA analyses, and the functional unit (FU) was 1 m^2 of gross floor area. The analysis was performed using a Cradle-to-Grave approach. The phases included in the assessment, A (production and construction), B (use and maintenance), C (end of life), and D (benefits beyond the system boundaries), are described more in detail in Fig. 1.

Software and Standards. OneClickLCA (OCL) software was used to quantify environmental impacts. The LCA method complies with the requirements of ISO 14040, ISO 14044, and European standards for the sustainability of materials and buildings EN 15804 + A2/AC and EN 15978. The assessment focused on GWP indicators to provide a transparent comparison of the climate change impacts of different materials. Four key indicators were analyzed according to methodological standards: GWP-total, GWP-fossil, GWP-biogenic, and GWP-LULUC.

Statistical analysis. A multi-criteria analysis (MCA) was used to comprehensively compare the environmental performance of five roof composition variants within the four GWP indicators monitored. This method allows alternatives to be evaluated based on multiple indicators simultaneously, providing a comprehensive view of the decision-making process and helping to identify the most environmentally suitable solution. The analysis was performed in MCA7 software using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. In the context of this study, this method means identifying the composition that minimizes negative environmental impacts (such as GWP-fossil) and maximizes positive benefits (such as GWP-biogenic). Four indicators were considered in the MCA analysis (GWP-total, GWP-fossil, GWP-biogenic, and GWP-LULUC). All four indicators were assigned the same weight (25%) with a total sum of 1, ensuring a neutral and balanced approach to assessing the various aspects of global warming potential.

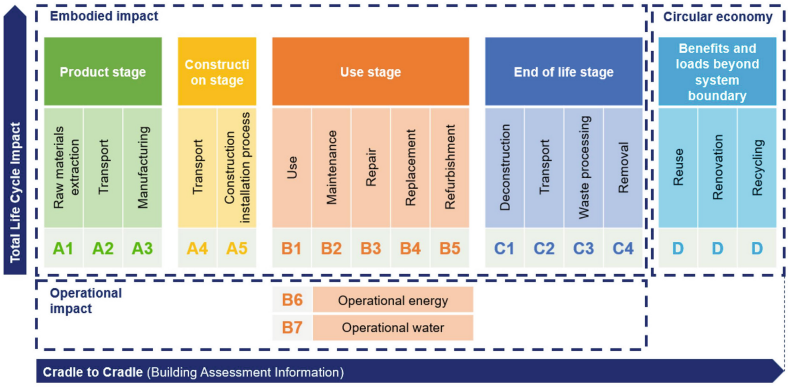
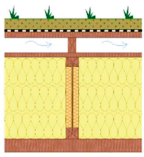


Fig. 1. System boundaries considered in the LCA analysis.

2.2 Life Cycle Inventory (LCI)

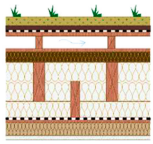
An LCI analysis was performed for five wooden flat roof variants designed to meet the Slovak passive building standard STN 73 0540-2, achieving a heat transfer coefficient U = 0.08 W/(m^2·K). Data was sourced from Ecoinvent, GaBi, and specific EPDs. For natural insulations (hemp, flax, cellulose), carbon sequestration was emphasized, while their higher specific heat capacity improves the building's summer thermal response compared to mineral wool. Vegetated variants (R1–R3) included maintenance and water requirements (modules B6, B7) based on Central European climate data in OCL software. The extensive green roof maintenance assumes two visits per year (weed removal, drain inspection), with irrigation water consumption modeled at 20 l/m^2 per year (July–August). All variants feature a ventilated air gap to remove moisture and protect moisture-sensitive natural insulation materials. Roof compositions are detailed in Table 1.

Table 1. Composition of wooden flat roofs.

COMPOSITION R1 – Mineral wool	*Thickness d[m]*	*λ [W/(m·K)]*	***U W/(m^2·K)***
Substrate	0.060	0.50	**0.097**
Waterproofing + geotextile	–	–	
Wooden formwork	0.027	0.13	
Ventilated gap – between 60 × 80	0.080	–	
DHF board – diffusion wood fiber board	0.015	0.10	
Mineral wool with PE between I-profiles	0.400	0.040	
CLT board 33 + 27 mm	0.060	0.13	
COMPOSITION R2 - Hemp	*Thickness d[m]*	*λ [W/(m·K)]*	***U W/(m^2·K)***

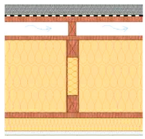
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Table 1. (*continued*)

Substrate	0.060	0.50	**0.081**
Drainage layer - expanded clay	0.030	0.11	
Waterproofing + geotextile	–	–	
OSB board 2 × 15 mm	0.030	0.13	
Ventilated gap - 60 × 80, á = 600 mm	0.080	–	
DHF board - diffusion wood fiber board	0.015	0.1	
Wood fiber board insulation	0.060	0.05	
Wood fiber insulation between KVH	0.140	0.04	
Hemp insulation between KVH 80 × 220	0.220	0.045	
Vapor barrier	–	–	
Wooden formwork	0.022	0.13	
Hemp insulation with PE between 60 × 80	0.080	0.045	
2 × 12.5 mm plasterboard	0.025	0.22	
COMPOSITION R3 – Sheep wool	*Thickness d [m]*	*λ [W/(m·K)]*	***U W/(m²·K)***
Substrate	0.060	0.50	**0.080**
Waterproofing + geotextile	–	–	
Wooden formwork	0.027	0.13	
Ventilated gap - between 60 × 60	0.060	–	
DHF board - diffusion wood fiber board	0.015	0.1	
Wood fiber board insulation	0.050	0.052	
Sheep wool between KVH 60 × 200	0.200	0.042	
Sheep wool between KVH 100 × 240	0.140	0.042	
OSB 3 board with glued joints	0.022	0.13	
Hemp insulation with PE	0.100	0.045	
Gypsum plaster board	0.015	0.22	
Clay plaster on reed mat	0.015	0.7	
COMPOSITION R4 - Cellulose	*Thickness d[m]*	*λ [W/(m·K)]*	***U W/(m²·K)***
Gravel	0.060	0.65	**0.084**
Waterproofing + geotextile	–	–	
OSB board 2 × 15 mm	0.030	0.13	
Ventilated gap - between 60 × 80	0.080	–	

(*continued*)

Table 1. (*continued*)

Wood fiber board - insulation	0.050	0.052	
Cellulose boards between KVH 120 × 280	0.280	0.04	
OSB 3 board with glued joints	0.022	0.13	
Blown cellulose between 60 × 140	0.140	0.039	
Gypsum fiber board 2 × 12.5 mm	0.025	0.32	
COMPOSITION R5 - Linen	*Thickness d [m]*	*λ [W/(m·K)]*	***U W/(m²·K)***
Gravel	0.060	0.65	**0.086**
Waterproofing + geotextile	–	–	
Wooden formwork	0.027	0.13	
Ventilated gap - between 60 × 80	0.080	–	
DHF board - diffusion wood fiber board	0.015	0.1	
Linen insulation between cabinet	0.360	0.04	
OSB 3 board with glued joints	0.022	0.13	
Linen insulation + PE between 60 × 80	0.080	0.04	
Plasterboard 2 × 12.5 mm	0.025	0.22	

3 Results and Discussion

An evaluation of five wooden flat roof compositions from LCA shows a significant advantage of natural insulants in terms of their ability to store carbon, with the most significant environmental benefit in the production phase (A1–A3) achieved by composition R2 with hemp insulation, which sequesters up to −102.13 kg CO_{2e}/m^2. Although the maintenance of green roofs increases their emissions, their environmental benefits are significantly higher. In terms of overall balance, the R4 composition with blown cellulose appears to produce the least emissions in GWP-total, but when the benefits of module D and high initial carbon sequestration are considered, all three natural variants (R2, R3, R5) are the best solutions for sustainable construction, significantly outperforming conventional mineral wool. The results for the impact categories are shown in Table 2 and Fig. 2. The GWP-fossil indicator represents the energy intensity of production and operation without considering the carbon stored in plants. The lowest emissions occur in the production phase (A1–A3) and are reported by the R4 composition with cellulose insulation (35.94 kg CO_{2e}/m^2), which confirms its low industrial intensity compared to R1 mineral wool thermal insulation (67.69 kg CO_{2e}/m^2), which requires energy-intensive extraction of raw materials.

Table 2. Results for impact categories.

Impact category	Unit	R1	R2	R3	R4	R5
GWP-total	[$kgCO_{2e}/m^2$]	563.18	564.35	548.48	54.94	61.38
GWP-fossil	[$kgCO_{2e}/m^2$]	563.07	564.16	548.17	54.79	61.29
GWP-biogenic	[$kgCO_{2e\ bio}/m^2$]	0.003	0	0	0	0
GWP-LULUC	[$kgCO_{2e}/m^2$]	0.109	0.173	0.289	0.132	0.088

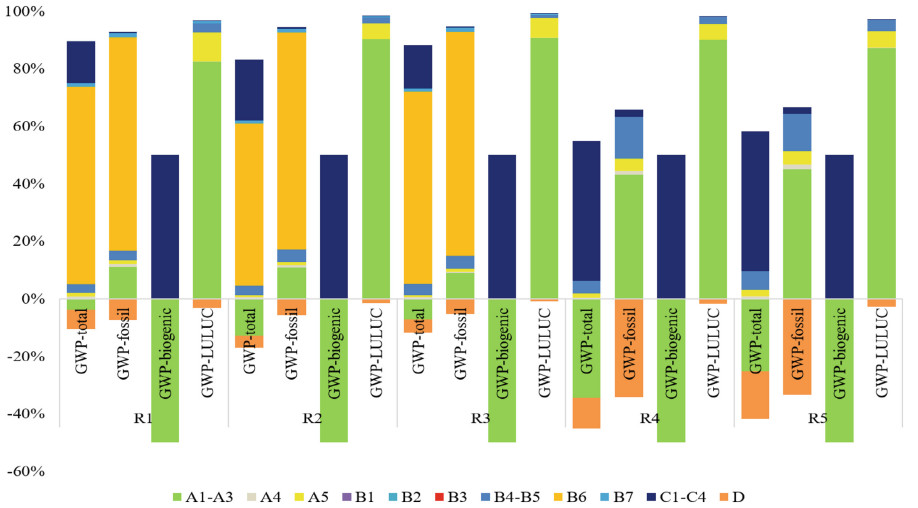


Fig. 2. Life cycle phase results for GWP impact categories in percentages (%).

In the variants of flat wooden roof structures with extensive vegetation (R1, R2, R3), emissions in the operational phase B6 and B7 are high (451.34 and 8.26 kg CO_{2e}/m^2 respectively), reflecting the fuel and energy consumption associated with regular maintenance and irrigation of vegetation. In terms of GWP-fossil, emissions are lowest for structures without a green roof (R4, R5), with cellulose thermal insulation remaining the most energy-efficient solution with minimal impact on the depletion of non-renewable resources. An evaluation of the thermal insulation materials used confirms the fundamental difference between conventional and natural insulators in terms of their environmental impact. Natural materials such as hemp (R2), sheep wool (R3), cellulose (R4) and linen (R5) demonstrate excellent carbon sequestration capabilities, which are reflected in the analysis by negative GWP-biogenic values. Hemp insulation (R2) achieves the highest contribution in GWP-biogenic, while blown cellulose (R4) dominates in energy efficiency in production in GWP-fossil. C The mineral wool roof variant (R1) is a conventional solution with high consumption of non-renewable resources and zero carbon sequestration, but offers good recycling potential in module D. In terms of operation,

green roof components in compositions R1–R3, despite higher emissions from maintenance, provide important ecosystem services such as evapotranspiration and water retention, which increase the overall sustainability of the solution beyond the GWP figures alone. Analysis of biogenic GWP confirms the key role of natural materials as temporary carbon storage reservoirs. The highest sequestration capacity is demonstrated by the R2 wooden roof structure with hemp insulation, which binds up to −167.39 kg CO_{2e}/m^2 during the production phase (A1–A3), which is almost double that of the R1 mineral wool structure (−93.14 kg CO_{2e}/m^2), where only the wooden load-bearing elements store carbon. Although this stored CO_{2e} is released back into the atmosphere when the structure is demolished at the end of its life cycle (C1–C4), thereby offsetting the biogenic carbon balance, the long-term incorporation of these materials into buildings is an effective way of decarbonizing the construction industry. Compositions with cellulose thermal insulation (R4) and hemp insulation (R2) thus provide a significantly higher initial environmental benefit in the form of a negative carbon footprint of the material phase compared to compositions with mineral wool. The GWP-LULUC analysis confirms that the impact of material compositions on the landscape is minimal in relation to the total carbon footprint, with the highest value in the production phase (A1–A3) being shown by the composition of the R3 flat wooden roof with sheep's wool thermal insulation (0.265 kg CO_{2e}/m^2). This slightly higher value compared to other insulants reflects the demands on agricultural land associated with livestock farming. On the contrary, the most soil-friendly option appears to be the cultivation of raw materials for the R5 flat wooden roof structure with linen insulation (0.079 kg CO_{2e}/m^2) and the R1 variant (0.093 kg CO_{2e}/m^2). In accordance with the study by Füchsl et al. [9], the analyzed compositions of wooden flat roofs with vegetation (R1–R3) show higher operational demands, but this is compensated by their contribution to the microclimate and rainwater management. At the same time, according to the findings of Llantoy et al. [10], the use of natural materials in the compositions of external walls provides a GWP-biogenic area. The results confirm that natural materials have a significantly lower GWP-fossil than conventional mineral wool, which is key to the decarbonization of the construction industry. The study also emphasizes the importance of assessing roofs over a period of 50 years or more, when the energy savings of vegetation layers become fully apparent.

The TOPSIS analysis confirmed that, when all GWP indicators are considered in a balanced manner, the most optimal solution is the R4 composition with cellulose thermal insulation. This variant came closest to the ideal with the lowest GWP-fossil emissions (A1–A3) and zero operational load (modules B6, B7). Other natural insulants were close behind, with hemp (R2), for example, achieving a high score thanks to its significant sequestration of biogenic carbon. The analysis thus confirmed a sustainability hierarchy in which natural materials (R4, R5, R2, R3) consistently dominate mineral wool (R1), which has high embodied energy and no carbon storage.

3.1 Limitations of the Study

Although this LCA study adheres to methodological standards, it is subject to several limitations and uncertainties associated with modeling assumptions. The first significant limitation concerns the end-of-life scenarios in modules C and D. The resulting biogenic

carbon balance (GWP-biogenic) is highly sensitive to whether natural insulation materials (hemp, linen, cellulose) will be landfilled, incinerated for energy recovery, or recycled in accordance with the principles of the circular economy following the demolition of the building. At the same time, it is necessary to emphasize the limitations of the life cycle assessment methodology itself, which focuses primarily on global warming potential (GWP) indicators. Green roofs provide key ecosystem services, such as mitigating the urban heat island effect through evapotranspiration and advanced stormwater management. In practice, these factors reduce the need for mechanical cooling of the entire building, which, in a comprehensive building energy model (excluding the roof structure), would lead to an additional reduction in operational CO_{2e} emissions.

4 Conclusion

A comparison of five compositions for wooden flat roofs confirmed that the choice of thermal insulation has a significant impact not only on thermal properties but also on the overall environmental footprint of a building. All variants achieved excellent heat transfer coefficient values, making them ideal for passive and zero-energy houses. However, from an LCA perspective, the most advantageous options are those with natural thermal insulation. Options using linen (R2) and cellulose (R4) as thermal insulation have a negative carbon footprint in phases A1–A3 due to their GWP-biogenic character. Hemp insulation (R2) has the lowest emissions. Blown cellulose (R4) achieved the lowest emissions in GWP-fossil, while its processing requires significantly less primary energy compared to conventional mineral wool (R1). Although variants with a vegetation layer (R1–R3) show higher values in the GWP-fossil analysis due to operational maintenance and water consumption, their benefit lies in reducing the urban heat island effect through evapotranspiration and rainwater management. The impact on land use change (GWP-LULUC) is low for all variants, with flax cultivation appearing to be the most soil-friendly (R5). Based on these results, it can be concluded that the combination of natural insulation materials (hemp and cellulose) with a vegetation layer can be considered the most environmentally optimal solution. This approach not only minimizes greenhouse gas emissions during the life cycle, but also actively contributes to the adaptation of buildings to climate change.

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Reducing Embodied Emissions in the EU Building Stock: Circular Economy vs. Alternative Strategies

Nicolas Alaux[1], Giovanna Cassavia[1], Giulia Pristerà[2], Karen Allacker[2], and Alexander Passer[1](✉)

[1] Working Group Sustainable Construction, Institute of Structural Design, Graz University of Technology, Technikerstraße 4, 8010 Graz, Austria
alexander.passer@tugraz.at

[2] Department of Architecture, Faculty of Engineering Science, KU Leuven, Leuven, Belgium

Abstract. Decarbonizing Europe's built environment requires tackling embodied greenhouse gas (GHG) emissions alongside operational energy use. Using the PULSE-EU building stock model, we quantify embodied GHG mitigation strategies across the EU-27 from the demand-side (circularity and sufficiency), as well as supply-side. The model dynamically links new construction, maintenance, renovation, and demolition activities to life cycle assessment results in a consistent framework until 2050. We compare (i) circular economy interventions (service life extension via renovation, vacancy reduction, efficient structural material use, and increased reuse and recycling facilitated by on-site waste sorting) against (ii) reductions in per capita space demand via higher use intensity of residential buildings, (iii) shifts to low-carbon bio-based materials (timber construction and bio-based insulation), (iv) improvements in material production processes (efficiency, alternative fuels, and innovative technologies such as carbon capture and storage), and (v) improvements in transport and construction processes (alternative fuels, machine optimization, and shorter transport distances). The results indicate that by 2050 circular economy measures can deliver the largest embodied GHG reduction (33%), followed by improvements in material production (32%) and lower per capita space demand (27%). Combining all strategies reduces embodied emissions by about 60% relative to a 2020 baseline, with less-than-additive effects due to overlapping savings. The findings underscore the primacy of circularity (especially avoiding new material demand) and the necessity of parallel supply-side decarbonization to reach substantial reductions. While results are reported for the EU-27, reductions vary across Member States, owing to differences in stock age, vacancy state, material mix, and potential for industrial change.

Keywords: Greenhouse Gas Emissions · Circular Building · Life Cycle Assessment · Embodied Carbon · Mitigation Strategies

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1 Introduction

Reducing greenhouse gas (GHG) emissions in the built environment is essential to achieving the European Union (EU)'s climate neutrality targets. While policy and research have traditionally focused on reducing operational emissions from buildings, interest in embodied emissions, those associated with the production, transport, construction, maintenance, and end-of-life treatment of materials, has increased in recent years [1]. This shift is driven by both improvements in operational efficiency and the projected expansion of the building stock, which increases demand for carbon-intensive construction materials such as cement, steel, and insulation products. Embodied GHG emissions from buildings and construction are now directly targeted in EU policies, in particular with the recast of the *Energy Performance of Buildings Directive* [2].

In this context, circular economy strategies have emerged as key levers for reducing material-related emissions by slowing, narrowing, and closing material loops [3]. These strategies encompass a broad range of interventions, including, for example, material substitution, reuse of building components, design for disassembly, service life extension, and reductions in material demand through changes in building use patterns [4]. Across sectors, circular economy measures have demonstrated substantial mitigation potential, with a recent literature review reporting an average relative reduction in GHG emissions of around one-third compared with baseline scenarios. Notably, the buildings and construction sector has been identified as one of the most promising areas, with relative reduction potentials averaging 48% [5].

Despite this potential, the current literature on circular economy and climate mitigation reveals important limitations [5]. First, existing studies are heavily skewed towards downstream measures, particularly recycling and waste management. In contrast, upstream strategies, such as demand reduction, material efficiency, reuse, and service life extension, remain comparatively underexplored, despite evidence suggesting they may offer equal or greater mitigation potential. Second, there is substantial heterogeneity in the definition of circular economy strategies, their modeling approaches, system boundaries, and assumptions, which makes it difficult to compare results with other mitigation strategies. Third, most studies focus on individual materials, products, or technical interventions rather than assessing integrated mitigation strategies across entire building stocks or comparing circular economy measures with alternative approaches, such as efficiency improvements.

This paper contributes to closing this gap by systematically evaluating the mitigation potential of circular economy strategies compared with alternative approaches for reducing embodied GHG emissions in the EU building stock. By quantifying the effects of circular economy strategies and alternatives in an integrated and consistent modeling approach that captures material flows, building stock dynamics, and life cycle emissions, this study provides new insights into the relative effectiveness of different mitigation strategies. In doing so, it aims to support evidence-based policymaking and contribute to the development of coherent strategies for achieving climate neutrality in the EU's built environment.

2 Methods

2.1 Building Stock Model

PULSE-EU is a high-resolution model of the EU-27 building stock that projects life cycle GHG emissions from 2020 to 2050 and simulates the extent to which different mitigation strategies can reduce these emissions [6, 7]. It links projected building stock dynamics, including new construction, maintenance, renovation, replacement, and demolition from the PULSE modeling logic, to life cycle assessment (LCA) results generated with the MMG-SLiCE framework [8, 9].

From a modeling perspective, PULSE-EU represents the existing stock through a comprehensive set of building archetypes that capture differences in age, size, construction methods, technical systems, and emission profiles. Archetypes are defined per EU Member State by clustering buildings across sector (residential vs. non-residential), building type (single-family houses, multi-family houses, apartment blocks, offices, education, healthcare, trade, hotels and restaurants, and other non-residential), and construction period. A total of 15,026 archetypes are used for modeling the EU building stock. Floor area data and typologies are aligned with the EU Building Stock Observatory [10] to ensure consistency and represent buildings as they exist today, whether original or already renovated.

Life cycle inventories are assembled via the SLiCE data model [8] and the KU Leuven MMG framework [9], following the modular EN 15978 approach [11] and a hierarchical decomposition from building to elements and materials. This framework attributes impacts to specific building parts and materials, and tracks when emissions occur across life cycle stages. The LCA follows the EN 15978 [11] and EN 15804 + A2 [12] standards, and uses generic inventory data from ecoinvent 3.6 [13] with the MMG impact assessment method [9].

2.2 Future Scenarios

Future scenarios are created by combining and deploying GHG emission reduction strategies. Strategy deployment in the model follows a structured, country-specific process. First, for each strategy, quantitative diffusion targets (e.g., how quickly it could spread through the building stock) are defined at three milestone years (2030, 2040, and 2050) with three ambition levels: low, medium, and high. Second, the capacity of each EU Member State to put these strategies into practice is assessed. This capacity rating, again low, medium, or high, captures local conditions such as resource availability, market readiness, and policy context. Both the quantitative diffusion targets and the capacity ratings are informed by the literature and refined through discussions with stakeholders. They are transparently reported in a previous publication [14], alongside with their theoretical GHG emission reduction potential.

Finally, we combine these two layers. For every country–strategy pair, the model selects the diffusion value that corresponds to that country's capacity level (low with low, medium with medium, high with high). This produces a single, integrated scenario where each Member State pushes each strategy to its plausible upper bound, ensuring the overall pathway is grounded in local constraints. All of the available strategies,

and the data used for their implementation (e.g., diffusion values for each decade), are summarized in a supplementary table (available in a public repository [15]). Due to the large amount of strategies and data collected, only a simplified overview is shown in Table 1. Interested readers are referred to these previous publications for more details on the strategies [7, 15]. In this study, we model a set of scenarios by applying the following combination of strategies:

- *CIRCULARITY*: circular economy interventions (service life extension via renovation, vacancy reduction, efficient structural material use, and increased material reuse and recycling facilitated by on-site waste sorting).
- *SPACE DEMAND*: reductions in per capita space demand via higher use intensity of residential buildings. This strategy is sometimes included under the umbrella of the circular economy, but considering its strong influence in our modeling approach, it is here considered as a separate scenario.
- *BIO-BASED*: shifts to low-carbon bio-based materials (timber construction and bio-based insulation).
- *MATERIALS*: improvements in material production processes (efficiency improvements, use of alternative fuels and innovative technologies such as carbon capture and storage).
- *PROCESS*: improvements in transport and construction processes (alternative fuels, machine optimization, and shorter transport distances).
- *ALL*: All of the above-mentioned strategies combined.

In these scenarios, circular economy measures are approached from a demand-side perspective (e.g., strategies that reduce the need for virgin material by slowing, narrowing, or closing loops). Although sometimes included under the umbrella of the circular economy, material and process-related changes denote supply-side decarbonization (not reducing demand *per se*), and the use of bio-based materials rather refers to material substitution. We therefore acknowledge that some measures are sometimes framed as circular, but we separate them here to keep levers analytically distinct.

Table 1. Example of strategies included in each scenario and diffusion potentials in 2050.

Scenario	Example of strategies included in each scenario (full list available online [15])	Diffusion in 2050 (low/medium/high)
CIRCULARITY	Percentage of empty dwellings which are renovated and put back to use.	15%/30%/45%
SPACE DEMAND	Percentage of reduction in per capita space demand compared to the business-as-usual projection (based on historical trends).	10%/20%/30%
BIO-BASED	Share of synthetic and mineral insulation materials substituted by bio-based materials.	20%/50%/80%

(*continued*)

Table 1. (*continued*)

Scenario	Example of strategies included in each scenario (full list available online [15])	Diffusion in 2050 (low/medium/high)
MATERIALS	Percentage of process emissions in cement production effectively captured and stored.	23%/42%/90%
PROCESS	Percentage of the transportation fleet using alternative fuels or electricity.	30%/60%/100%

3 Results and Discussion

3.1 Embodied Emission Trajectories

Circular economy measures can deliver the largest embodied GHG reduction by 2050 compared with 2020 (33%), followed by improvements in material production (32%) and lower per capita space demand (27%), as shown in Fig. 1. The use of bio-based materials reaches a non-negligible 12% embodied emissions reduction, while improvements in transport and construction processes only reach 6%. Differences in timing of implementation can also be observed. While circular economy interventions and per capita space demand reduction have a rapid emission reduction potential, by 2030, the potential for additional reductions decreases with time. On the contrary, improving material production has more gradual benefits, reaching additional similar GHG emission reductions over time.

These scenarios also target different life cycle stages of the buildings. For example, the circularity scenario almost entirely reduces demolition-related emissions by 2050, and considerably reduces construction-related emissions, but a trade-off is observed for renovation-related emissions. On the contrary, the materials scenario reduces both construction, renovation, and use phase related emissions. Combining all strategies reduces embodied emissions by about 60% by 2050, with less-than-additive effects due to overlapping savings. This complementarity of the different strategies, from the time of implementation to impact of the different life cycle stages, highlights the necessity of parallel demand and supply-side approaches to reach substantial emission reductions.

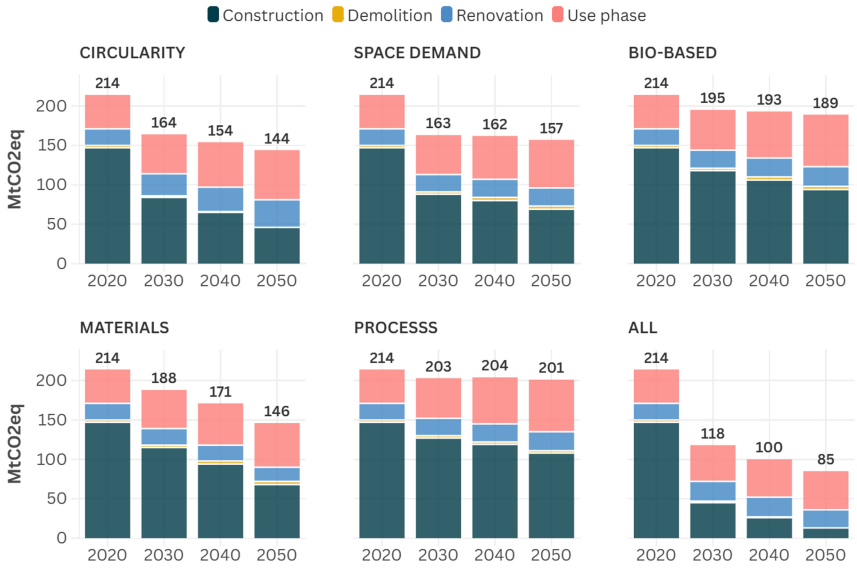


Fig. 1. Annual embodied GHG emissions from building construction (A1–5), demolition (C1–4), renovation (B5), and use (B2, B4), for each of the scenarios. Figure made with flourish.studio.

3.2 Differences Across EU Member States

The impact of circular economy interventions (e.g., from the circularity scenario) varies across EU Member States, owing to differences in building stock age, density, vacancy state, material mix, and potentials for industrial change, as shown in Fig. 2. Higher GHG emissions reductions (more than 41%) can be achieved as a result of circular economy interventions in Spain, the Netherlands and Bulgaria, while lower reductions (less than 16%) can be seen in Hungary and Finland. More modest reductions (16 to 41%) can be reached in the other EU Member States. For Member States with lower reduction potentials, it is worth noting that only Hungary and Finland reach very low reduction potentials (less than 7%), while all other countries reach at least 16%, highlighting that, although other Member States might have higher mitigation potentials, circular economy strategies are still quite promising.

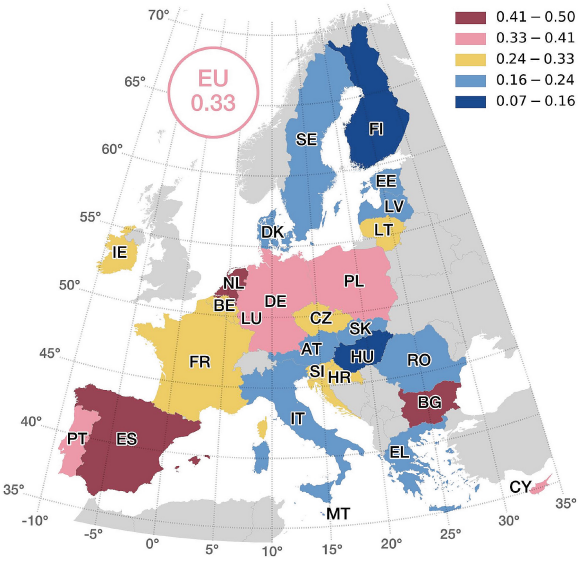


Fig. 2. Relative reduction in embodied GHG emissions by 2050 compared with 2020, for the circularity scenario, reported for each Member State and for the EU average. A 0.4 relative reduction means that embodied emissions of this country were 40% lower in 2050 than in 2020 with this particular scenario. The administrative areas used in this figure are from GADM (v2.8).

Both the Netherlands and Spain exhibit emission reduction potentials exceeding 45% under circular economy strategies. This high potential can be attributed to three structural characteristics: (i) very high population density, particularly in the Netherlands (in comparison to Finland), which amplifies the gains from more intensive use of the existing building stock and from material reuse, thereby lowering embodied emissions; (ii) a relatively balanced split between embodied and operational emissions (approximately 50% each) combined with high vacancy rates, particularly in Spain, but also in Bulgaria and Portugal, conditions under which circular economy measures deliver especially large benefits; and (iii) high per capita emissions, as in Luxembourg, Germany, and Poland, which increase the absolute scope for emission reductions.

3.3 Model Limitations

To develop future projections, building stock models use input data, such as information on building archetypes or life cycle scenarios, and dynamic parameters, including construction rates, which are inherently uncertain and challenging to predict. These uncertainties should be acknowledged when interpreting the results. In addition, this study does not include the potential rebound effects or unexpected dynamics from the implementation of the strategies, for which further empirical evidence is required to improve modeling. For example, reducing per capita space demand also has resilience implications, for which other aspects might be considered. An increase of ceiling height

could be necessary to reduce overheating while increasing spatial quality and construction adaptability. Similar considerations can be made for vacancy, and considering the typology or location of the vacant buildings in more detail could change these results.

4 Conclusion

Combining demand- and supply-side measures can reduce embodied GHG emissions from EU buildings by about 60% by 2050 relative to 2020. Circular economy actions provide the largest single potential (33%), followed by improved material production (32%), reduced per capita space demand (27%), bio-based substitution (12%), and construction/transport improvements (6%), with circularity and per capita space demand reduction delivering early gains while improvements in material production develop steadily over time. Reduction potentials vary across Member States, underscoring the need for tailored national roadmaps. Results should be interpreted in light of modeling uncertainties and potential trade-offs.

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From Material Cadastre to Data-Driven Innovations

Georg Shiller(✉) and Karin Gruhler

Leibniz Institute of Ecological Urban and Regional Development, 01217 Dresden, Germany
g.schiller@ioer.de

Abstract. Construction industry consumes the largest share of resources worldwide. Natural resources are predominantly used for this purpose. There is comprehensive knowledge about the availability and deposits of these resources. The situation is different for anthropogenic resources incorporated into existing buildings. Until now, little was known about the extent, composition and dynamics of these already used building materials. In recent years, however, a number of studies have been presented to explore and map these materials in existing buildings. This provides important information to support circular approaches in construction. But how can this information be used to support circular action? This article presents the development of a national materials register designed to enable circular construction stakeholders to access the information and develop it further in their own business models. The data set is presented in terms of its content and spatial resolution, and initial examples are given of how it is being used and developed by circular construction stakeholders.

Keywords: Material Cadastre · Data driven Innovation · Circular Construction

1 Introduction

The development of the built environment goes hand in hand with a constant demand for building materials. This will double worldwide over the next three decades [1]. Today, our built environment, i.e. buildings and infrastructure, already consumes around 50% of global resources and 25–40% of global energy [2] and generates 15–40% of global waste [2].

Buildings shape the visual character of cities and constitute a central component of the built environment as residential, office, public, and commercial structures. While many of these buildings are publicly accessible and can be located via digital mapping services, little is known about their material composition. Information on the materials used, their quantities, provenance, and the ecological impacts associated with their production, transport, and processing often remains inaccessible. Nor is so-called 'grey energy' – that is, the amount of energy consumed in the production of building materials and during the construction of a building– usually visible [3, 4]. This results in a significant data gap in the material metabolism of urban systems.

In fact, such information does exist: every building is based on planning processes in which material decisions are made and documented. However, these data are rarely

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centrally accessible or systematically analyzable. Instead, they have been stored in a decentralized manner over decades—for example, in analog building records, on storage media such as floppy disks or CD-ROMs, on local hard drives, or within various cloud systems [5]. Consequently, material-related information about the built environment is distributed across a heterogeneous digital and physical archive whose structure reflects the historical evolution of construction practices. As buildings age, access to information regarding their material composition typically becomes increasingly difficult.

Yet it is precisely these data that are essential for unlocking a significant resource: the materials embedded in buildings and infrastructures constitute a substantial reservoir of anthropogenic raw materials [6, 7] that can be systematically exploited within the framework of urban mining concepts.

The digital representation of this anthropogenic material stock in three-dimensional maps [8], equipped with integrated processing and analytical functionalities, establishes a critical data foundation for a wide range of potential applications. This enables diverse stakeholder groups to develop their own analyses, applications, and planning tools on this basis. The spectrum of possible use cases is broad and depends largely on the type, scope, and quality of the integrated information and datasets. This paper provides an overview of these aspects and discusses associated challenges and fields of application.

2 Material Cadastre Covering the Building Stock of a Whole Nation

With the Material Cadastre Germany (Fig. 1), the authors and colleagues provide, for the first time, a nationwide, comprehensive database on the material composition of the building stock across all municipalities in Germany [9].

Approximately 20.8 billion tonnes of construction materials are embodied in Germany's roughly 51.6 million buildings. Concrete dominates this material stock, accounting for 46%, followed by calcium silicate brick and clay brick, each contributing just under 10%. Renewable materials such as wood, reed, or straw play only a marginal role, comprising around 1% of the total mass.

By linking cadastre data with regional construction and demolition data [10], it becomes possible to estimate both the potential for recycling processes and the future demand for construction materials in new construction and refurbishment. In addition, anticipated volumes of construction and demolition waste can be projected comprehensively across the entire territory.

Linking the material data with life cycle assessment datasets allows for inferences regarding embodied greenhouse gas (GHG) emissions [11, 12]. Theoretically, the production of the materials used in construction would release approximately 2.7 billion tonnes of GHGs—roughly four times Germany's annual emissions. This highlights the substantial value contained in materials already built into the urban environment. If these materials can be reused or their service life extended, additional GHG emissions can be avoided.

The cadastre is based on a typological approach applying the bottom-up principle [13]. In this framework, building stocks are recorded, assigned to corresponding typologies [14], linked with indicators for construction materials and embodied emissions, and used to calculate material composition and emissions.

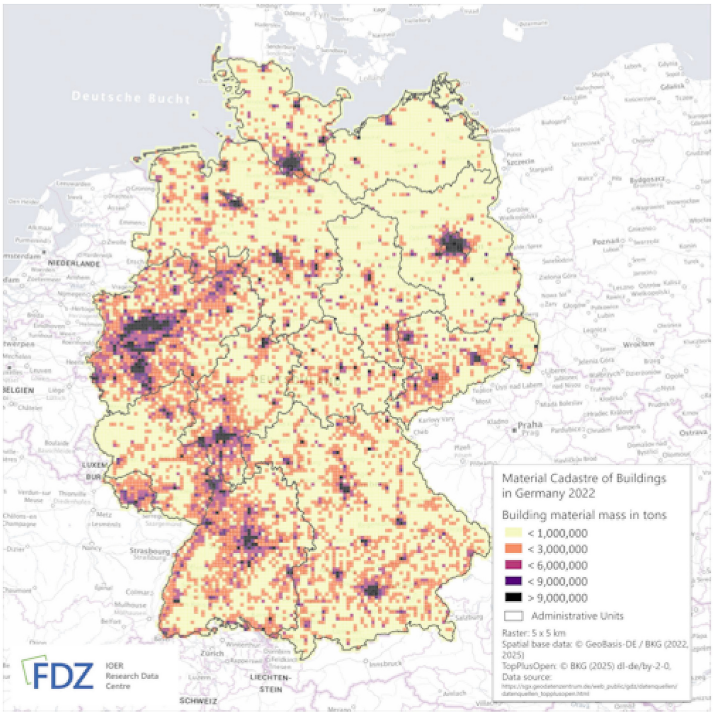


Fig. 1. Material Cadastre Germany – material mass of buildings [data source: 9].

The basis for capturing the building stock is a comprehensive 3D building model of Germany's building inventory [15], provided by the Federal Agency for Cartography and Geodesy (BKG). These digital models contain information on building function, which is used for the typological classification of buildings. This approach ultimately produces a reliable representation of the volume of each building by building type—from single-family houses to office buildings and logistics halls.

The types and quantities of materials typically used per cubic meter of building volume are expressed through so-called material indicators. The development of these indicators was based on extensive long-term research, in which numerous individual buildings were analyzed to represent the characteristic construction methods of each building type. Material use for each component, from the foundation to the roof, was recorded and aggregated at the level of building typologies [14, 16] (Fig. 2).

In total, 44 construction material groups are differentiated, with the relative use of materials varying by building type—for example, higher proportions of concrete in industrial buildings, and greater use of wood or brick in single-family houses. The material indicators are accessible via the IOER's Built Environment Information System [16] (Fig. 3). The complete dataset of the Material Cadastre Germany is made available through the open-data repository of the IOER Research Data Center [17].

The typology-based approach, however, does not replace detailed analyses at the individual building level. This method does not allow for precise determination of the

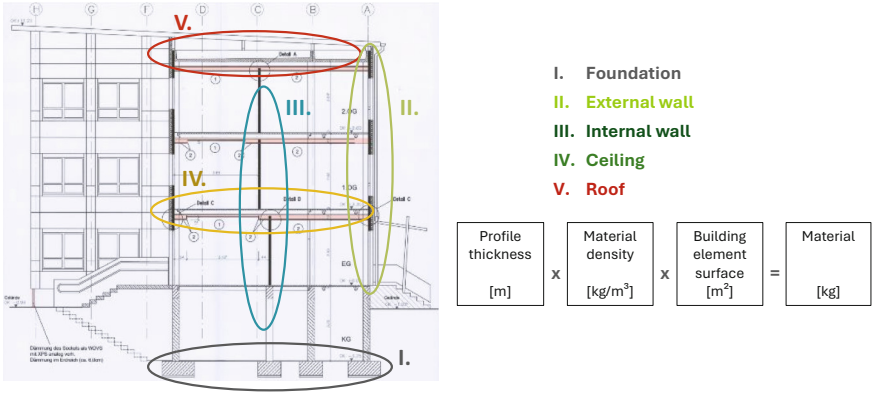


Fig. 2. Development of specific material indicators based on the analysis of planning documents for representative buildings (changed according to [13])

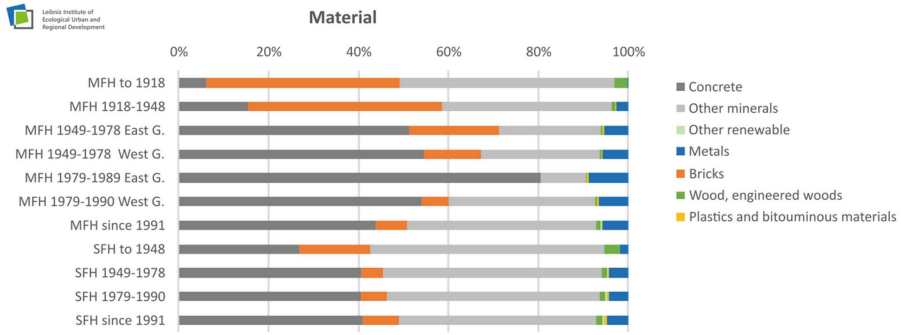


Fig. 3. Material indicators (MI) of typical German (G.) multi-family houses (MFH) and single-family houses (SFH) by main material groups – examples from ISBE [16].

material composition of specific buildings but provides indicative reference values. Nevertheless, its utility is significant, as the cadastre reduces the costs of data acquisition, increases transparency regarding material flows within the building stock, and enables new business models—from the development of building passports to the support of pre-demolition audits and digitally assisted deconstruction planning. Municipalities, planning offices, property owners, and consulting firms can directly use the provided data or complement it with their own analyses. Similarly, recycling companies can use the information to more accurately estimate which secondary raw materials will be regionally available.

3 Materia Cadastre: Knowledge Base for Stakeholder Activities

Research achieves its full impact only when it is translated into real-world practice, particularly in the construction industry. What knowledge can be extracted from extensive datasets on buildings? What value does a digital map offer, and how can these insights be implemented effectively in practical contexts?

The publication of the national Material Cadastre has attracted significant attention in Germany. Several initial applications have been developed based on this dataset, which are exemplarily outlined here. For instance, the start-up company Concular [18] used the openly available Material Cadastre dataset to develop an Urban Mining Cadastre and now provides advisory services to cities and municipalities. In the city of Osnabrück, e.g., questions were posed regarding the materials, stored energy, and reusable resources contained within the urban environment. With support from the start-up, Osnabrück's entire building stock was analyzed using the Urban Mining Cadastre, aiming to make the city's material composition visible and thereby establish a foundation for circular building management. Similarly, the platform supported the city of Stuttgart within the framework of a climate innovation initiative, enabling a comprehensive analysis of its building stock through the Urban Mining Cadastre. To facilitate low-threshold adoption of the digital platform in the public sector, initial workshops were held to systematically analyze objectives and potential applications [19]. An example from Prague takes a similar approach and examines the role that material inventories can play in supporting pre-demolition audits [8]

The practical value of digital data ultimately lies in its implementation on construction sites. However, translating the environmental impact analysis of an entire city's building stock into concrete decisions for individual buildings requires intermediate steps. Here, the interface of the Urban Mining Cadastre with digital planning data for individual buildings plays a crucial role. For older buildings, such data is often unavailable, and the dataset must be supplemented manually when action is required at the respective building. Because the cadastre links each building to an accessible and editable dataset, this interface has been established. Furthermore, Concular's life cycle assessment software (Fig. 4) enables material decisions to be evaluated already during the planning phase, allowing different renovation scenarios to be compared and the identified potential for material reuse to be verified and utilized in a subsequent process according to DIN SPEC 91414. The so-called Pre-Deconstruction Audit (PDA) represents the first step toward actual reuse at the level of individual buildings. Similar examples can also be found among other market players or local governments that utilize the IOER data from the material cadastre, such as Madaster Germany, which advises states and local governments on circularity based on the dataset of the cadastre described above [20].

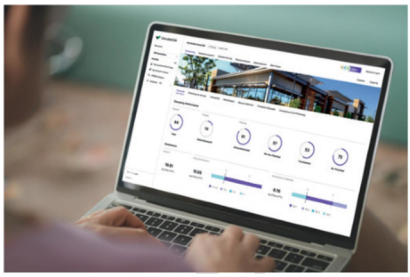


Fig. 4. Softwaretool CircularLCA.that is based on Material Cadastre data to support pre demolition audits for buildings (source: [18])

4 Limitations and Uncertainties

The typological approach underpinning the cadastre is subject to fundamental limitations. The material indicators used are based on average values for building types, age categories or usage categories, and thus abstract away from the actual heterogeneity of the real building stock. This simplification leads to uncertainties, particularly in high-resolution, location-specific analyses. As spatial resolution increases, so does the tendency for errors [21]. This can be countered by further refining the typologies through additional characteristics like building age. However, the fundamental limitation of typological approaches remains [14].

When considering the transferability of material indicators used to other spatial contexts or locations, it is important to take into account the impact of these contexts on construction methods and, consequently, on the material composition of the buildings – for example, by considering geologically induced natural hazards or socio-cultural conditions – as this helps to narrow down uncertainties [8, 22].

The issue of hazardous substances is also of particular interest in the context of recycling practice [23]. Type-based material flow analyses are limited in terms of the quality of potential secondary materials, particularly because they are based on highly aggregated average values and do not explicitly reflect the heterogeneous and pollutant-related material composition of real buildings [14]. As a result, relevant contamination—particularly from pollutants associated with the age of the building and the type of materials used—is not taken into account [24]. Recent research shows that hazardous substances in building stocks (e.g., asbestos and PCBs) are increasingly being assessed using machine learning models trained on building registers and demolition inventories, enabling probabilistic risk mapping at building level, whereas traditional material flow analysis lacks the chemical and spatial resolution required for such assessments [25].

5 Conclusion

Digital datasets on the anthropogenic material stock can stimulate innovations and circular construction activities when they are well-founded, reliably provided, easily accessible, and equipped with interfaces for integration with advanced applications and combination with other datasets. Such datasets can also enable the development of

economically viable business models, as illustrated by the examples presented in this paper.

The role of science is to develop methodologies, generate suitable data, and make these data available. However, this alone does not guarantee a profound transformation of the construction sector. The risk remains that applications will be limited to isolated projects or niche innovations. Therefore, science also has a responsibility to actively shape the intended transformation in order to enhance societal impact. This entails addressing the question of how such a transformation can be guided. Transdisciplinary approaches are required, and levers for change must be identified and promoted, for example by providing knowledge and data to be incorporated into comprehensive data ecosystems shaped by both science and practice. The development of niche areas should be encouraged, as should the creation of the necessary regulatory and policy frameworks, for example in the form of regulations or specific strategies. - because one thing is clear: the mere provision of data is not sufficient.

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Integrating Digital Technologies for Automated Circularity Assessment of Construction Products

Giuliana Parisi[1(✉)], Eleonora Giuffrida[1], Stefano Cascone[2], and Rosa Caponetto[1]

[1] University of Catania, Catania 95125, Italy
giuliana.parisi@phd.unict.it
[2] Politecnico di Torino, Turin 10129, Italy

Abstract. In the construction sector, circular approaches are increasingly recognized as a key strategy to reduce demand for primary raw materials while supporting economic development. Concurrently, the adoption of digital tools enables automated collection and management of information, thereby improving the ability to evaluate alternative scenarios and enhance environmental performance. This study presents a decision support system (DSS) that includes an automated calculation of the Circularity Level (LC) of products and services and a BIM-based digitalization of product data, enabling circularity information sharing across the construction supply chain. The LC is an index derived from a set of 68 circularity indicators specified in UNI/TS 11820, aligned with ISO/TC 323 Circular Economy and the EU Level(s) framework. In this research, an Excel-based calculator is developed to automate LC calculations from manufacturer-provided data. Subsequently, an LC Report is automatically generated via APIs, providing supporting documentation to ensure data traceability and to identify potential areas for improvement. Finally, a bidirectional information flow is established between Excel and Autodesk Revit via Dynamo parametric scripts, enabling automated customization of product-related BIM objects. The proposed workflow enables scalability across different product categories and regulatory requirements. The challenges associated with LC improvement strategies are identified, and future research directions are outlined to leverage AI-based predictive tools to support the evaluation of alternative scenarios. Moreover, the workflow should be tested through a case study to assess its validity in a real-world context. This research advances the digitalisation of circularity assessment, supporting green and digital transitions in the construction sector.

Keywords: Building Information Modeling · Visual Programming Language · Sustainable Development · Circular Economy · Green Transition

1 Introduction

Over the past decades, the limitations of the traditional linear economy (LE) model are increasingly highlighted by rising resource demand and waste production. LE is based on intensive resource use and short product life cycles and is considered incompatible

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with international sustainability objectives. In this context, a paradigm shift from the LE to the circular economy (CE) is required, aiming to close material loops, reduce waste production and enhance the value of resources throughout the life cycle [1].

In response to these challenges, several regulatory frameworks have been developed to support the transition toward more sustainable models, such as the United Nations' Agenda 2030 [2] and the EU Level(s) framework [3]. Specifically, at the international level the International Organization for Standardization (ISO) has established the technical committee ISO/TC 323 "Circular economy" [4], which has defined standards such as ISO 59004 [5], ISO 59010 [6] and ISO 59020 [7], respectively addressing circular economy principles, business model transition and the assessment of circularity performance. These standards have also been adopted at the European and national levels. Within this framework, the Italian standard UNI/TS 11820 [8], further detailed in Sect. 2, is introduced as an operational tool for assessing the Circularity Level (LC) of products and services.

In parallel, within the construction sector, the digital transition requires the structured management of information flows related to circularity assessments to support the integration of environmental sustainability and technological innovation. In this context, digital technologies are adopted, among which Building Information Modeling (BIM) is recognized as an enabling methodology for managing information throughout the entire building life cycle [9]. To improve interoperability and data management efficiency, BIM is integrated with Visual Programming Languages (VPL), such as Dynamo, which enables the development of parametric scripts to facilitate the extraction and integration of the data required to assess circularity performance across the life cycle of products [10].

However, several gaps remain in the development of digital workflows for circularity assessment. Circularity evaluation processes are often carried out manually, resulting in procedures that are difficult to replicate and to verify, thereby limiting the standardization and traceability of results [11]. Moreover, when such assessments are digitalized, they are frequently conducted through workflows that integrate BIM with external software, such as Life Cycle Assessment (LCA) tools (e.g., SimaPro, Athena Impact Estimator) and Excel databases [12]. This approach generates interoperability issues across platforms and challenges in managing information flow and preventing data loss. Although tools such as VPLs enable the development of parametric scripts to support specific analyses, their application to circularity assessment remains limited and dependent on customized configurations [13].

To address these gaps, this research develops a Decision Support System (DSS) to automate the calculation of product LCs and their subsequent BIM-based digitalization, thereby enabling the integration and sharing of information along the supply chain among different stakeholders. The resulting digital tool, developed through the automated integration of Microsoft Excel, Microsoft Word, Autodesk Revit and Dynamo, meets the requirements of UNI/TS 11820. However, due to the presence of a parametric core, the proposed methodology is scalable and can potentially be adapted to other regulatory contexts.

2 UNI/TS 11820: European Context and Key Features

In this research, the focus on UNI/TS 11820 is driven by its role as a detailed tool within the regulatory framework for assessing circularity. Specifically, the UNI/TS 11820 is developed considering the work of the ISO/TC 323 "Circular economy" technical committee [4–7], as reported in the Introduction section. Furthermore, within the European context, UNI/TS 11820 aligns with the EU Level(s) framework, which promotes the assessment of building sustainability across its life cycle, specifically with Macro-objective 2 "Resource Efficient Circular Material Life Cycles" [3]. In detail, UNI/TS 11820 specifies a set of 68 CE indicators, classified according to their applicability to products (P), services (S) or both products and services (P/S), used to evaluate, through a final score, the product or service's LC. The final score does not establish minimum circularity thresholds but provides an overall evaluation of the level achieved.

Moreover, UNI/TS 11820 distinguishes three evaluation approaches: semi-quantitative, in which measurements are carried out using predefined thresholds; quantitative, based on numerical values; and qualitative, in which binary criteria are used to verify specific conditions. Furthermore, the indicators are grouped into six thematic categories that assess circularity from complementary perspectives across the entire organizational system. An additional classification is provided by subdividing the indicators into Core, Specific and Rewarding. The Core category includes mandatory indicators. The Specific category includes indicators that must be completed unless they are deemed technically inapplicable. Finally, the Rewarding category includes optional indicators that increase the final circularity score. A specific weight is also assigned to each indicator type for the calculation of the final score: 1 for core and specific indicators and 0.5 for rewarding indicators.

Figure 1 shows the classification of UNI/TS 11820 indicators across the six categories, distinguishing between Core, Specific and Rewarding Indicators.

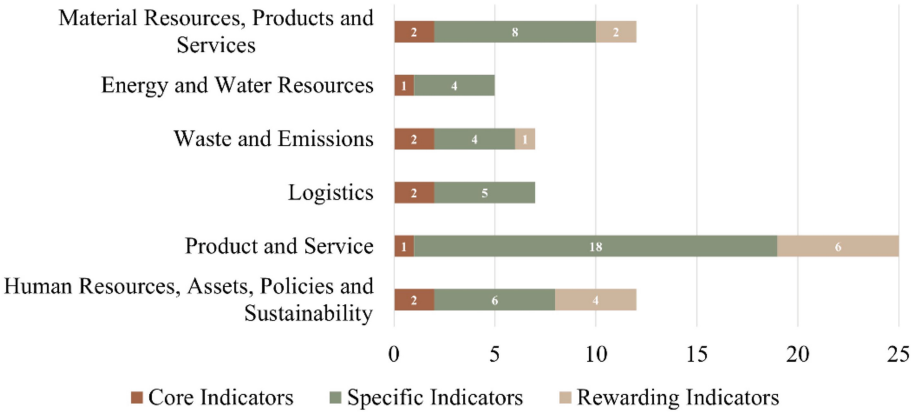


Fig. 1. Classification of UNI/TS 11820 indicators by thematic category and type (Core, Specific and Rewarding).

The "Product and Service" category includes the highest number of indicators, with a prevalence of specific and rewarding indicators, highlighting the central role assigned to circular product and service design and life cycle management. The "Human Resources, Assets, Policies and Sustainability" category presents a structured set of indicators, underscoring the importance of the organizational and strategic dimensions in implementing circular-economy principles. Conversely, the categories "Energy and Water Resources", "Waste and Emissions" and "Logistics" include fewer indicators, mainly specific, focusing on operational aspects. Finally, the "Material Resources, Products and Services" category includes core, specific, and rewarding indicators, underlining the importance of material flow management in circularity assessment.

In conclusion, the LC is defined as a percentage index obtained by aggregating the scores of the Core, Specific and Rewarding indicators, expressed as the ratio of the achieved score to the maximum theoretical score, ranging from 0% to 100%.

3 Framework for Digital Circularity Assessment

UNI/TS 11820 provides a framework for assessing circularity. In the construction sector, where many materials are evaluated and documented throughout the building lifecycle, the digitalization of the standard, particularly through BIM-based processes, becomes a key aspect. Figure 2 summarizes the digital workflow presented in this research to automate LC calculation and integrate product-related circularity data into BIM.

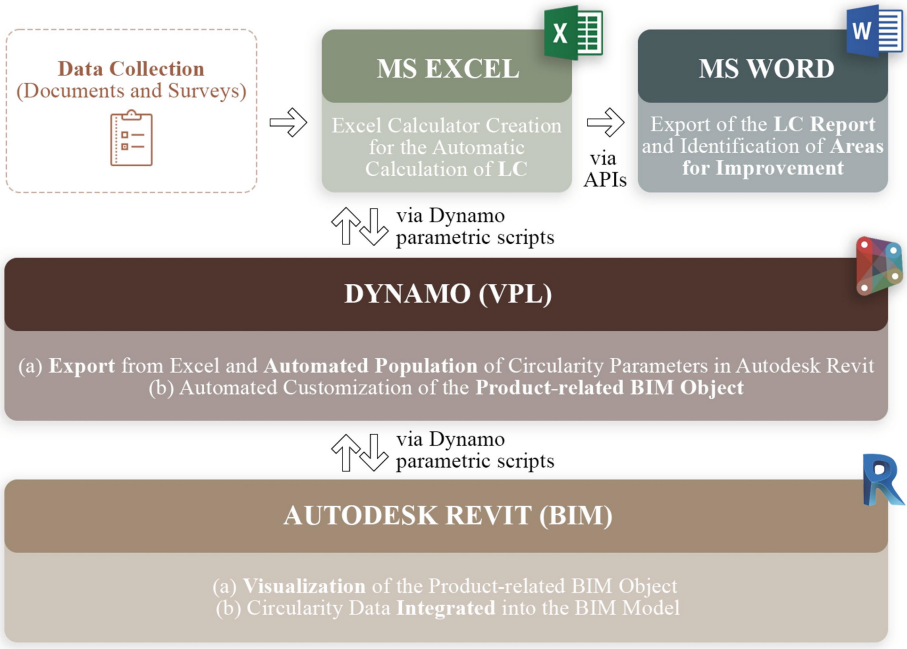


Fig. 2. Overview of the Proposed Methodology.

Specifically, an Excel-based calculator automates the calculation of circularity indicators and the generation of the LC value for both products and services, integrating survey and documentation data. The results are then automatically transferred to MS Word, where the LC Report is generated in accordance with UNI/TS 11820. In the following step, a bidirectional workflow between Excel and Autodesk Revit is implemented through Dynamo, enabling the automated creation of BIM object parameters and the integration of circularity data for construction products. Interoperability is ensured through APIs and Dynamo scripts, while the parametric structure allows replicability and scalability across different regulatory contexts.

The methodological validation of the proposed tool is supported by the detailed technical specifications, calculation procedures and weighting criteria of the circularity indicators defined in UNI/TS 11820. These specifications provide a methodological reference for implementing the automated calculation process, aligning the digital workflow with the standard's requirements and ensuring the consistency and reliability of the generated LC values and reports.

3.1 Automated LC Assessment and Report Generation

In an initial phase, the study develops an Excel-based calculator that automates the calculation of circularity indicators selected from manufacturer-provided inputs and returns the LC value.

The digital tool is organized into a series of spreadsheets. On the first sheet, guidelines for completing the form are provided to help users enter data correctly. A second group of sheets summarizes the 68 indicators, reporting their main characteristics described in Sect. 2, including the description, reference category, type (Core, Specific or Rewarding), weight and evaluation approach (qualitative, quantitative or semi-quantitative). Users can automatically select the indicators to include in the LC calculation based on the product or service under assessment. The third group of sheets constitutes the key section of the calculator, since the calculation method for each indicator is automatically defined and implemented, and both the indicator's specific and weighted values are automatically obtained. The calculation of this set of indicators represents a preliminary phase to the automatic calculation of LC, which is subsequently determined according to Eq. (1):

$$LC = \frac{\sum_{i=1}^{n} c_i + \sum_{j=1}^{m} s_j + 0,5 \sum_{k=1}^{f} p_k}{c + s} \quad (1)$$

where c_i is the value of the i-th core indicator, s_j is the value of the j-th applied specific indicator and p_k is the value of the k-th compiled rewarding indicator; n is the number of evaluated core indicators, m is the number of applied specific indicators and f is the number of compiled rewarding indicators; c is the total number of core indicators provided and s is the total number of applicable specific indicators [8].

To automatically generate the required LC Report as supporting documentation to ensure data traceability, the obtained results are imported into MS Word via APIs, allowing the direct extraction of the report. The document also provides automatic generation of a radar chart, enabling visualization of the overall score across the six indicator categories. This graphical representation allows potential areas for improvement to be identified and supports optimizing the LC value.

3.2 VPL-Based Customization of Product-Related BIM Objects

To digitalize product circularity indicators and make them available to stakeholders in BIM, a parametric Dynamo script is developed to enable automatic customization of Product-Related BIM Object parameters (Fig. 3).

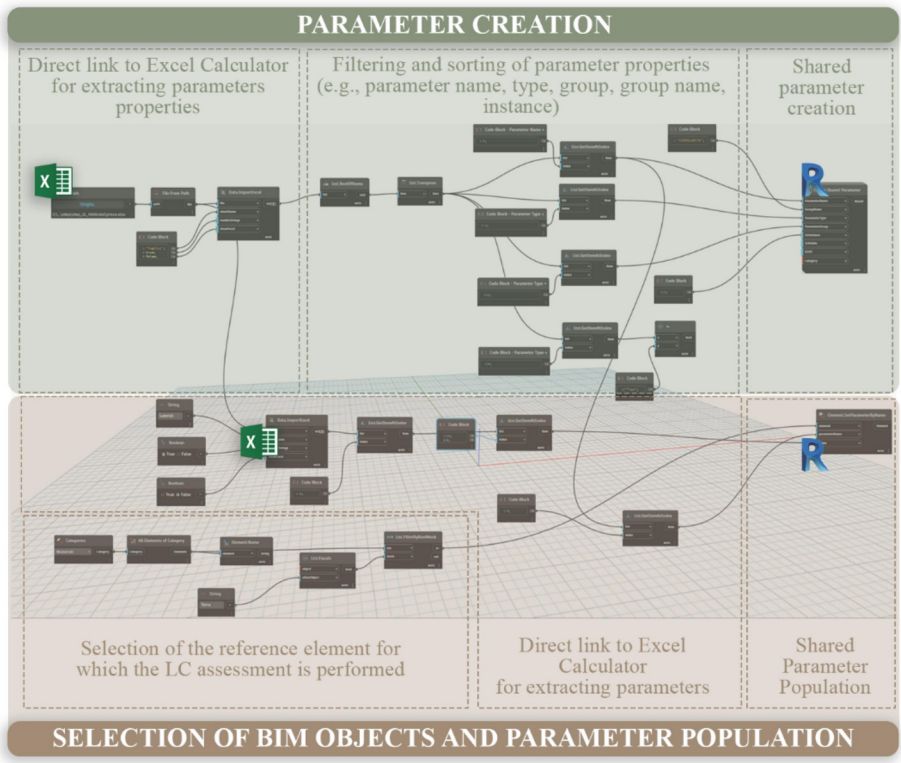


Fig. 3. Dynamo Parametric Script for the Automatic Creation of Shared Parameters in Revit (Green) and the Population of Circularity Data in BIM Objects (Orange) through Integration with the Excel Calculator.

The first section enables the automatic creation of parameters in Autodesk Revit. The script is configured with a direct link to the Excel Calculator to extract parameter properties through the nodes "File.Path" and "Data.ImportExcel". The extracted properties include the parameter name (e.g., LC_Value), parameter group, parameter type, reference category and the Type/Instance property. Subsequently, these data are filtered and sorted using nodes from the Dynamo package "Crumple". The resulting data are then used as inputs for the "Parameter.CreateSharedParameter" node from the "Genius Loci" package, through which shared parameters are automatically created in Autodesk Revit.

The second section of the script enables selection of the element or material for which the LC assessment is performed, using nodes such as "Element" and

"List.FilterByBoolMask". At the same time, to import the parameter value, a connection to the Excel Calculator is established. Specifically, the reference sheet is selected through the "String" nodes, while the coordinates of the cell containing the value to be assigned to the parameters are specified through the "List.GetItemAtIndex" and "Code Block" nodes. The BIM object, the parameter value and the name of the parameter to be filled are then provided as inputs to the "Element.SetParameterByName" node, through which the automatic population of the parameter within the BIM model is performed.

4 Research Implications and Future Perspectives

The proposed workflow ensures a scalable and replicable tool for assessing and digitalising circularity. The research develops a digital workflow integrating MS Excel, MS Word, Autodesk Revit and Dynamo. The Excel-based calculator automatically computes the LC for both products and services, while BIM-based digitalisation is applied to construction products. This configuration allows circularity data to be automatically transferred and updated within BIM objects. This is relevant to construction materials, as regulations require evaluating multiple materials in buildings and using BIM. Integrating circularity information into BIM supports systematic data management across the lifecycle and can be scaled to other sectors.

A specific focus is placed on the workflow's operational structure. The Excel-based calculator features a user-friendly interface to facilitate data entry by manufacturers, while the calculation rules align with the regulatory framework, ensuring consistency between the implemented methodology and existing requirements. Interoperability is ensured through a bidirectional, continuous data flow enabled by APIs and Dynamo parametric scripts.

However, some limitations are identified in this study, opening directions for future research. First, the developed digital tool needs to be tested and validated through case studies to assess its effectiveness in a real operational context. In this regard, the proposed workflow has been developed as an operational background study of the ITER Project and will be applied in the related case study, where earthen plasters enhanced with by-products from the agricultural and stone supply chains are implemented. Another limitation concerns the fact that input data in the Excel calculator are currently entered manually by the user. The integration of Artificial Intelligence (AI) methods, particularly Large Language Models (LLMs) based on Natural Language Processing (NLP), could enable the automatic extraction of information from technical product documentation. Finally, the DSS is structured as a parametric basis for future AI-based optimization tools that aim to improve the LC value by suggesting alternative scenarios.

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Digitalisation and Automation: BIM-Based Approaches, Digital Twins, Digital Passports, AI-Powered Tools, and Decision-Support Systems

BIM Framework in Projectual Phase Using Balanced Scorecard

Luiz Pedro de Melo Cesar[1(✉)], Maria Vitoria Duarte Ferrari[1], Thaís Oliveira Chaves Fontes[1], Leonardo da Silveira Pirillo Inojosa[1], Raquel Naves Blumenschein[1], Antonio Carlos de Oliveira Miranda[1], Cynthia Nojimoto[1], Luciane Cleonice Durante[2], Félix Alves da Silva Alves Júnior[1], and Kamila Karen Fernandes Gomes[1]

[1] Universidade de Brasília, Brasília, DF 70910-900, Brazil
lula@unb.br
[2] Universidade Federal de Mato Grosso, Cuiabá, MT 78060-900, Brazil

Abstract. The escalating global focus on sustainability and circularity in the built environment calls for innovative approaches to evaluate and optimize building performance across its life cycle, particularly during the critical early design phase. To address this challenge, strategic governance and robust performance measurement are essential. Accordingly, this paper introduces a novel Building Information Modeling-based Balanced Scorecard framework to govern and measure BIM implementation quality in building design projects. Drawing on the well-established Balanced Scorecard approach, it breaks down BIM's strategic importance into four interconnected perspectives: Virtual Model, Technology, Processes and Documentation, and Technical Team. The resulting BSC-BIM framework thus enables strategic planning, BIM maturity benchmarking, and enhanced decision-making. Moreover, by providing defined principles, criteria, and verifiable indicators, it empowers project teams to monitor process standardization, information quality, technological interoperability, and organizational shifts toward digital adoption, ultimately supporting whole-life cycle performance and sustainable design. In turn, this ensures high-quality, sustainable design-phase information for subsequent analyses, operations, renewals, and circular economy practices in construction.

Keywords: Building Information Modeling (BIM) · Balanced Scorecard (BSC) · Whole-Life Cycle (WLC) · Sustainable Design; Performance Metrics

1 Introduction

The Civil Construction Industry (CCI) requires integrated products, processes, and services, along with a shift in mindset to consider the entire building life cycle—from concept and construction to operation and demolition. BIM emerges as a key methodology, several studies highlight BIM benefits regarding interoperability, collaboration, and process optimization within the construction industry [1, 2, 5, 6]. Defined by ISO 19650-1:2018 [3] as the use of a shared digital representation of a built asset, BIM integrates

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functional, geometric, and material data across project stages. Its dimensions include 3D modeling for virtual construction and documentation, 4D integration of scheduling, and 5D linkage of cost information.

Strategic planning tools such as SWOT, SSP, and especially the Balanced Scorecard (BSC) [7–10] support performance measurement and systemic integration in large-scale projects. BSC has been applied to engineering and adapted to contexts like sustainability certifications (e.g., BREEAM) and major projects such as the London Olympics and Brazil's PISAC. In Brazil, BIM-based frameworks combined with BSC have guided multidisciplinary design, incorporating architecture, engineering systems, and cross-cutting themes like sustainability, accessibility, innovation, and ergonomics throughout the building life cycle.

2 Theoretical Framework of Balanced Scorecard

The Balanced Scorecard (BSC) is a dynamic planning and management methodology that supports continuous monitoring, evaluation, and feedback throughout the design process. It enhances strategic visualization, decision-making, communication, and performance measurement while aligning goals, indicators, and action plans with broader objectives. Functioning as an integrated dashboard, the BSC structures project monitoring systems and promotes continuous improvement, learning, and multidisciplinary coordination. Its comprehensive approach strengthens project management efficiency and supports the achievement of positive and measurable outcomes, such as:

- Strategic mapping, as it is one of the tools used to implement a strategy by identifying elements and stakeholders within a given process, including their responsibilities.
- Definition of strategic objectives, which act as previously established guidelines aimed at long-term aspirations;
- Establishment of clear performance indicators, which are easy to obtain and measure, allowing the assessment of progress toward strategic objectives;
- Setting of targets with specific outcomes, where targets serve as identifiable temporal milestones along the path toward achieving each strategic objective.

The BSC also serves as an instrument of internal and external communication, aligning strategies and individual, organizational, and interdepartmental initiatives, while taking into account all levels of information within a continuous learning process [7]. The methodology has also been applied in industrial engineering and organizational management contexts [11]

2.1 BIM (Building Information Modeling)

BIM can be understood differently depending on context: for governments, it is a policy to improve construction processes; for economists, a tool to boost industry efficiency; and for engineers, a project methodology. According to ISO standards, BIM is a 3D digital representation of a construction project containing information for building and operation. This model, created with architectural, structural, and systems software, is stored in a shared data environment and enables virtual construction, issue detection,

and decision-making. Research on automated BIM generation and interoperability has also demonstrated the growing importance of digital data integration and parametric information management [4, 5].

ISO 19650-1:2018 [3] defines specific BIM roles such as information manager, delivery manager, lead designer, task team manager, interface manager, and BIM authors. BIM processes are dynamic, evolving through implementation to optimize deliverables, including file sharing, information control, workflow management, training, and model development. These processes must be documented to ensure good practices. BIM is built on three dimensions—technology, processes, and people—supported by standards and best-practice documents like manuals, flowcharts, and diagrams.

BIM software solutions vary in features, affecting interoperability, production, and organizational capacity. Because BIM models are complex and data-heavy, they require advanced hardware and IT infrastructure. BIM processes involve multidisciplinary teams and demand collaboration, training, and adaptation. According to ISO 19650-1 [3], BIM defines roles such as information managers, delivery managers, lead designers, and BIM authors. These processes, covering data sharing, workflow management, training, and model development, must be formally documented to ensure standards and best practices.

The three fundamental BIM dimensions, technology, processes, and people, support the creation of procedures, standards, and management documentation. Such documentation was organized into three categories for the BIM scorecard: (a) strategic and pre-contract planning documents; (b) management and coordination documents for people and processes; and (c) technical documents supporting deliverable production, including manuals for nomenclature, coordination, federated models, parametric objects, file management, and design processes. Together, these categories structure BIM implementation and support project management, coordination, and quality control.

3 Methodology

The use of the BSC organizes all design related and methodological expectations of the project production process. It is important in a BIM implementation context, because helps define goals and processes of design and management. The BIM process organizes design information through computational tools originated from various design disciplines, as well as other disciplines throughout the entire process, with impacts across the whole building life cycle. To greater clarity with BIM-based project organization process, was adopted a similar method of scorecard proposed by Kaplan and Norton [7], primarily adapted by BRE sustainability assessment framework developed for the PISAC project [12]. This experience is grounded in numerous applications of BSC-like analytical frameworks worldwide [13]. Therefore, the model served as a basis for developing discussions with PISAC researchers, with the aim of constructing a broader strategic planning framework (beyond sustainability) within a BIM context, while simultaneously refining the methodological tool itself. The discussion had three stages: (a) interviews with each discipline to identify activities, according to the proposed methodology; (b) mapping relations among activities in order to establish the necessary integrations of the overall process; and (c) validation of the methodological matrix encompassing all disciplines. The process provided an empirical review, identifying and mapping requirements

that support the organization of resources and processes, with different perspectives and objectives, and integrating requirements along a timeline. This process provides a guideline for integration and, ultimately, is a framework for organizing design process and project execution monitoring.

The proposed framework systematized information into analytical categories structured through categories, principles, criteria, descriptions, indicators, verifiers, and references. The methodology was collaboratively discussed with researchers and refined through a series of internal multidisciplinary workshops, supported by theoretical, normative, and legal references. The validation process focused on the collective review and refinement of the proposed framework elements, including categories, principles, criteria, indicators, verifiers, and reference parameters. Rather than conducting a quantitative simulation, the study adopted a qualitative and collaborative validation approach, in which the applicability and coherence of the framework were assessed through technical discussions and interdisciplinary review meetings developed within the scope of the research project.

The results follow the proposed structure. The Table 1 presents the identified categories

The proposed Scorecard framework was validated through a series of internal workshops conducted with the multidisciplinary teams involved in the project development process, including architecture, complementary engineering disciplines, technical specifications, cost estimation, institutional security, BIM coordination, and environmental comfort. The workshops were carried out in up to two meetings with each team coordination, enabling a collaborative review and refinement of the elements composing the Scorecard structure, such as categories, principles, descriptions, indicators, verification criteria, and reference parameters.

The validation process aimed to ensure that the proposed framework comprehensively addressed key dimensions related to sustainability, accessibility, ergonomics, energy and water efficiency, and innovation within a BIM-based project management context. The process involved multidisciplinary technical teams composed of architects, engineers, BIM coordinators, and project specialists participating in up to two review meetings per discipline. The framework elements were evaluated according to applicability, interoperability, information management relevance, and compatibility with BIM-based workflows (Table 2).

It is important to emphasize that the study did not involve quantitative simulations or performance testing procedures. Instead, the validation was conducted qualitatively through interdisciplinary technical review processes and collaborative workshops developed within the scope of the research project.

Table 1. Categories identified.

Principles	Description
Category: Virtual Model This category consists of the integrated development of multiple disciplines simultaneously, monitored at each stage of the building project. Development is carried out in three dimensions, enabling visualization and continuous improvement of the building.	
Creation of the BIM model:	Addresses the definition of characteristics and criteria for BIM modeling of the de-signed buildings. The resulting model should be a digital version identical to the constructed building and should be used in the stages of design, planning and construction site management, building operation and maintenance, demolition, dismantling, and retrofit.
Design coordination	Defines the parameters necessary for information sharing among different teams.
BIM library	Establishes aspects for creating a repository of parametric elements that will serve as the basis for project development. The BIM library brings together materials, components, equipment, frames, and other elements used by the design disciplines, including the appropriate information and shared within a single database.
As-built updates in the virtual model	Refers to the need to plan cadastral updates of BIM-integrated projects in order to record modifications that occur throughout all phases of the building's life cycle. The objective is to enable accurate assessment of the condition of systems, allowing performance assessment and analysis of the technical and financial impacts of changes required over the life cycle.
Category: Technology This category involves defining and organizing the technical parameters necessary for the simultaneous sharing of projects within a BIM process. BIM-based project development depends on compatible and integrated technological and methodological resources.	
Software interoperability	Addresses the requirements for technological compatibility among different software applications. Design disciplines may use specific software tools; however, they must be able to exchange digital information completely and without loss of content.

(*continued*)

Table 1. (*continued*)

Principles	Description
Definition and sizing of appropriate hardware	Addresses the technical aspects of hardware configuration required for BIM project development and performance.
Common Data Environment (CDE)	Addresses aspects related to a shared environment for receiving information and storing contributions and deliverables from multiple disciplines in an organized and accessible manner. The CDE must be continuously managed to: ensure data accessibility and security, thereby supporting efficient project development.
Category: Processes and Documentation This category focuses on the functional organization of information, with the aim of standardizing production procedures and ensuring proper data, process, and product storage.	
Project process management	Addresses issues related to mapping and monitoring project activities.
Information management	Addresses issues related to communication, information flow, and information quality.
Monitoring of deliverables	Addresses aspects related to monitoring technical quality and the delivery of products.
General documentation	Addresses issues related to the proper organization and storage of documents.
Category: Technical Team This category focuses on identifying key aspects for the selection and formation of the technical team.	
Selection and organization of the technical team	Addresses aspects related to selecting and structuring technical teams according to the profiles required for BIM project development.
Assignment of responsibilities	Addresses the allocation of responsibilities to each individual within the teams, with the aim of identifying those responsible for each task and deliverable.
Cultural change	Addresses issues related to the individual adaptation required to carry out the BIM-based design process.

Table 2. Framework Application and Validation Example.

Category	Principle	Example of Indicator	Example of Verifier	Validation Approach
Virtual Model	Design coordination	Federated model integration	Coordination reports	Reviewed in interdisciplinary workshops
Technology	Software interoperability	IFC compatibility	Shared model exchange	Evaluated during BIM coordination meetings
Processes and Documentation	Information management	Communication flow	Meeting minutes and CDE records	Assessed collaboratively by project teams
Technical Team	Assignment of responsibilities	Responsibility matrix	BIM execution documentation	Validated with multidisciplinary coordinators

4 Conclusion

In conclusion, the proposed scorecard-like methodology integrated with BIM demonstrated potential as a management and planning support tool for multidisciplinary design processes. The collaborative validation process enabled the identification of relevant relationships among technical teams, project workflows, responsibilities, and information management requirements within BIM-based project environments.

Although the framework was not quantitatively tested through simulation or operational performance assessments, the internal multidisciplinary workshops contributed to refining and validating the methodological structure, supporting its applicability as a qualitative framework for organizing BIM-related processes, documentation, and strategic planning activities.

Furthermore, the structure supported the planning of project stages, workflows, and operational sequences, facilitating greater control over schedules, requirements, and expected outcomes. The integration of categories, principles, criteria, and indicators strengthened the capacity to monitor performance and detect inconsistencies at early stages. However, it is important to emphasize that the study did not advance toward the development of quantitative scoring systems, resulting in an evaluation framework that remained predominantly qualitative in nature. Even so, as a flexible and adaptive framework, the proposed BSC-oriented approach demonstrated significant potential to optimize BIM-based project management and enhance efficiency, integration, and strategic alignment within complex engineering and architectural projects.

This study presented a model in a similar format of a scorecard, based on the categories identified in the BIM design phase. The categories are related to the BIM dimensions of technology, people and processes, which generate procedures, standards, and best practices in the form of documentation. The scorecard itself can be considered part of these procedures, as it enables the evaluation of the design process and supports the

structuring of actions, assists decision-making, provides greater control over strategies, and helps identify strengths and weaknesses. The main contribution of this work is the proposal of a scorecard-like structure organized into categories for BIM in the design phase. The methodology supports the structuring of the BIM adoption process, as it encourages the definition of strategies for implementation based on its core dimensions (people, technology, and processes). It is important to emphasize that the structure is flexible and can (and should) be adapted to structural, political, and economic changes, which are common in an innovation-driven environment such as BIM. The scorecard-like methodology combined with BIM enabled a paradigm shift in the design process for project teams, as it allowed, within a shorter time frame, the analysis of formal and conceptual aspects, the identification of formal inconsistencies, and potential normative and behavioral gaps among the professionals involved in the projects. Ultimately, it facilitated the management process, especially during the phases of organizing and integrating design disciplines.

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Nature-Based Intelligence (NBI) for Climate-Resilient Urban Infrastructure: A GeoAI Decision-Support Engine

Volkan Türkbay[1], Onur Kaplan[2(✉)], Gordana Kaplan[2], and Alper Çabuk[3]

[1] Software Developer - Freelancer, Eskişehir, Türkiye
[2] Institute of Earth and Space Sciences, Eskişehir Technical University, Eskişehir, Türkiye
onur_kaplan@eskisehir.edu.tr
[3] Department of Architecture, Faculty of Architecture and Design, Eskişehir Technical University, Eskişehir, Türkiye

Abstract. Mitigating the pressures that climate change and the increasing frequency of natural hazards impose on urban infrastructure requires decision processes that can integrate heterogeneous evidence, quantify uncertainty, and remain operational under incomplete or conflicting data. This paper presents the architecture of a reliability-centred GeoAI decision support engine, the Nature-Based Intelligence (NBI) Geo NLP Orchestrator, developed within the EU-funded EPD Net project. NBI operationalises a risk-informed planning logic consistent with the hazard, exposure, vulnerability, and capacity framing used in disaster risk reduction [1, 7] and with the climate risk perspective emphasised for cities and critical infrastructure [2]. The engine ingests multi-disciplinary data streams, ranging from macro-socioeconomic indicators to environmental and hazard-related platforms, and processes numerical and textual evidence in parallel. "NBI Core" computes a cross-source consensus value and assigns a propagation-based reliability score that quantifies the trustworthiness of the resulting synthesis. "GeoResolver" produces location-specific environmental risk diagnostics at the local scale, while "AGIForecastEngine" learns from historical records to generate interpretable linear trend baselines relevant to infrastructure decisions. The workflow presented in this paper operationalises this claim through explicit hazard–exposure–vulnerability–capacity (HEVC) screening, two compact scoring equations, an Eskişehir pilot demonstration, and validation by triangulation, plausibility testing, sensitivity checks and data-lineage control.

Keywords: Nature-Based Intelligence · GeoAI · urban resilience · disaster resilient infrastructure · decision support systems · reliability scoring · EPD Net

1 Introduction

Climate change has become a foreground stressor on urban infrastructure, reshaping design thresholds, maintenance burdens, and failure cascades across interdependent networks. The most consequential shift is not merely that hazards are intensifying,

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but that exposure and vulnerability are accelerating precisely where institutional capacity is weakest. IPCC AR6 WGII states directly: "the most rapid growth in urban vulnerability and exposure has been in cities and settlements where adaptive capacity is limited" [2]. Infrastructure planning must therefore engage with socio-economic conditions and governance constraints, not only with engineering specifications. Nature-based solutions (NbS) offer a planning pathway that can align climate adaptation, ecological resilience and disaster risk reduction. NbS are defined as actions to protect, manage and restore ecosystems while addressing societal challenges and generating well-being and biodiversity benefits [3]. Yet NbS benefits are not automatic; their reliability and cost-effectiveness depend on context, maintenance capacity and evidence quality [4]. Urban resilience questions require evidence with different temporal scales, spatial resolutions and validation regimes; APIs and open platforms frequently supply data that are stale, inconsistent or semantically misaligned. What is needed is an orchestration layer that treats data as contestable evidence, fuses numerical and textual sources, and quantifies reliability under contradiction and incompleteness.

This paper introduces the NBI Geo NLP Orchestrator, developed within the EU-funded EPD Net project, as a reliability-centered GeoAI decision-support engine for climate-resilient urban infrastructure. The engine formalises three commitments: risk is treated as a dynamic signal; cross-source consensus is computed across heterogeneous evidence; and trustworthiness is reported through a propagation-based reliability score. GeoResolver binds diagnostics to place, while AGIForecastEngine provides transparent trend baselines for scenario reasoning. The following sections position NBI within DRR, NbS and GeoAI, describe the methodological core, and discuss conditions for institutional use in high-stakes planning.

1.1 Background/Related Work

UNDRR frames disaster risk assessment as contingent on prevailing hazards and on patterns of population and socioeconomic development [1, 7, 8], so hazard layers alone cannot represent risk when exposure, vulnerability and capacity are moving targets. Social vulnerability research shows that demographic, socio-economic and built-environment conditions shape who is harmed and who can recover [11]. NbS must be effective and adaptive while delivering co-benefits [3], yet reliability and cost-effectiveness remain context dependent [4]. GeoAI expands computability from complex geomatics data but intensifies evidence-governance demands under heterogeneity and scale effects [5]. The gap is architectural: decision support needs an orchestration layer that binds a planning question to relevant evidence, fuses numerical and textual signals, computes a defensible synthesis, and discloses reliability under contradiction and incompleteness.

1.2 Nature-Based Intelligence as a Decision Support Language

NBI is defined as a reliability-centered GeoAI decision support paradigm for infrastructure planning. It orchestrates nature-based, hazard-related and socio-economic evidence; fuses heterogeneous numerical and textual sources; and quantifies trustworthiness through a propagation-based reliability score. The definition is constrained by DRR risk grammar, where risk depends on hazards, exposed assets, vulnerability and capacity [1,

7, 8], and by NbS validity conditions requiring interventions to be effective, adaptive and beneficial for people and biodiversity [3]. NBI therefore treats provenance, consistency and uncertainty as planning objects. Its contribution is not a catalogue of NbS measures or a black-box predictor, but an auditable reasoning layer that translates a planning question into a location-bound diagnostic, computes consensus, and signals when evidence is weak, stale or contradictory. The operational loop has three layers: signal extraction, evidence interpretation and scenario baselining. These are implemented through the orchestrator, NBI Core, GeoResolver and AGIForecastEngine.

2 System Architecture of the NBI Geo NLP Orchestrator and Pilot Operationalisation

2.1 Architectural Overview and Design Rationale

The NBI Geo NLP Orchestrator is designed as an evidence-driven decision support pipeline that begins with a planning question and ends with a reliability-signalled set of diagnostics and scenario baselines. The central architectural choice is to treat the question as an executable specification. This is dictated by DRR risk grammar: if the question is underspecified, the workflow defaults to convenient data rather than relevant evidence, producing outputs that may be computationally coherent yet decision-irrelevant. The second architectural choice is to make reliability a computed output rather than an implicit assumption. This is motivated by the empirical reality of open data ecosystems: sources are heterogeneous in temporal coverage, spatial granularity, and validation regimes. The system therefore assumes inconsistency as a normal condition rather than an exceptional failure mode. The orchestrator resolves three properties for each query: the risk domain, the spatial scale, and the time horizon required for planning relevance. This creates a stable interface between institutional decision needs and heterogeneous evidence streams, guarding against the common failure mode in which a vague question triggers a technically impressive but semantically misaligned output. Once the workflow is resolved, the orchestrator activates multi-disciplinary evidence ingestion integrating nature-related indicators, hazard and environmental signals, and socio-economic descriptors, because DRR definitions explicitly embed development patterns into risk assessment [1]. The system ingests numerical time series, semi-structured event feeds, and unstructured or lightly structured textual sources. The design constraint is harmonisation: evidence arriving with different temporal granularities, inconsistent units, and ambiguous geographic references must be transformed into a comparable internal representation without silently discarding uncertainty, which is why NBI binds ingestion tightly to the reliability layer rather than treating data acquisition as a separate stage. For risk assessment tasks, the workflow is decomposed into hazard, exposure, vulnerability and capacity components rather than treating hazard intensity as a proxy for risk.

2.2 NBI Core: Consensus Computation as Evidence Fusion

NBI Core performs cross-source synthesis by computing a consensus value across heterogeneous evidence streams, preventing single-source dominance and stabilising outputs in the presence of partial disagreement. In a planning context, this is not an exercise in statistical elegance but in institutional defensibility: if two sources disagree on

an environmental stress indicator or on the socio-economic baseline, the engine must represent the disagreement, incorporate it into synthesis, and communicate it through reliability scoring. Consensus computation is used as a controlled mechanism for producing a decision-relevant summary in the presence of heterogeneous evidence. The propagation-based reliability score is the epistemic anchor of the architecture: it tracks source support, spatial-temporal alignment, timeliness and disagreement as evidence is transformed and combined. Reliability is not treated as a fixed source attribute, because a source can be locally valid and globally misleading, current in one domain and stale in another, or coherent alone but contradictory in combination. Outputs with weak support are therefore downgraded rather than allowed to become apparently authoritative recommendations. GeoResolver protects the workflow against scale mismatch by ensuring that diagnostics remain legible at the scale of action, where exposure is defined by the presence of people, infrastructure, services and ecological assets in hazard-prone areas.

2.3 AGIForecastEngine: Interpretable Trend Baselines for Scenario Reasoning

AGIForecastEngine provides linear trend projections derived from historical records for variables relevant to infrastructure planning. These outputs are explicitly baselines, not deterministic forecasts. Linear trends are used because they are transparent, rapidly falsifiable and useful for comparing scenarios under constrained evidence, whereas more complex models can create a false sense of precision when data quality is uneven. The forecast layer is coupled to the reliability layer: weak or inconsistent evidence triggers limited-confidence signalling and shifts the output toward diagnostic stability rather than speculative extrapolation. This supports NbS evaluation by making interventions comparable as alternatives rather than presenting them as generic defaults [3, 4].

2.4 Safety-Constrained HEVC Screening, Pilot Operationalisation and Validation

NBI treats risk assessment as a safety-constrained screening problem, not as automated hazard labelling. For each spatial unit i, the workflow separates four normalised 0–1 components: hazard intensity H, exposure of people, infrastructure and services E, vulnerability of exposed elements V, and adaptive capacity C. The integrated screening score R is computed as in Eq. (1)

$$R_i = 0.30H_i + 0.25E_i + 0.25V_i + 0.20(1 - C_i) \tag{1}$$

The weights are not claimed as universal constants; they are a transparent default used for the pilot and can be recalibrated by the competent authority. Reliability score Q is reported separately as in Eq. (2)

$$Q_i = S_i^* A_i^* T_i^* (1 - D_i) \tag{2}$$

where S is source support, A is spatial-temporal alignment, T is timeliness and D is disagreement penalty. Thus, a high-risk output is not accepted merely because a hazard layer is intense; it also requires exposed assets, vulnerable conditions, insufficient capacity and adequate reliability. Three operational gates prevent unsupported outputs

from becoming planning advice. The scope gate requires an explicit location, scale, risk domain and time horizon. The evidence gate requires at least two independent evidence streams for infrastructure-relevant interpretation. The confidence gate classifies outputs as actionable screening evidence only when $Q_i \geq 0.60$; outputs with $0.50 \leq Q_i < 0.60$ are flagged for expert review, and outputs with $Q_i < 0.50$ are treated as provisional. These thresholds follow the risk-management logic of documenting criteria, uncertainty and review triggers rather than silently converting weak evidence into recommendations [9, 10]. A compact Eskişehir city-center pilot demonstrates the computation. Values are not statutory hazard values; they are reproducible 0–1 screening scores derived from open spatial proxies and the NBI workflow to show how HEVC decomposition, reliability scoring and prioritisation operate across distinct planning conditions (Table 1).

Table 1. Eskişehir pilot HEVC screening and reliability demonstration

Pilot unit	HEVC and reliability values	Screening interpretation
Porsuk corridor	H = 0.78; E = 0.82; V = 0.64; C = 0.48; R = 0.70; Q = 0.72	High priority; requires municipal GIS review
Emek	H = 0.61; E = 0.88; V = 0.86; C = 0.42; R = 0.74; Q = 0.68	High priority; cooling-refuge and schoolyard greening
Gökmeydan	H = 0.58; E = 0.81; V = 0.82; C = 0.45; R = 0.70; Q = 0.66	High priority; heat-health corridor
Sazova–Sarısu	H = 0.80; E = 0.52; V = 0.48; C = 0.62; R = 0.57; Q = 0.70	Medium priority; retention and blue-infrastructure pilot
Şeker/industrial edge	H = 0.66; E = 0.74; V = 0.58; C = 0.40; R = 0.65; Q = 0.64	Medium-high priority; green buffer and runoff control

Validation is bounded to diagnostic defensibility. Internal tests perturb missing inputs, source conflict and spatial scale; cross-source checks test consensus stability; plausibility checks test conformity with disaster-risk logic; and one-at-a-time sensitivity varies each HEVC weight by $\pm 10\%$. Data integrity records source, access date, spatial reference, temporal coverage, unit, transformation and proxy status.

3 Conclusion

This paper introduced Nature-Based Intelligence as a reliability-centred GeoAI decision support engine for climate-resilient urban infrastructure, implemented through the NBI Geo NLP Orchestrator. The motivation is a structural mismatch between how risk is defined in disaster risk reduction and how decision support is commonly implemented in practice. UNDRR frames disaster risk assessment as contingent on prevailing hazards and on "the patterns of population and socioeconomic development" [1]. If this condition is taken seriously, hazard-centric outputs and single-stream analytics are insufficient for infrastructure planning, because they fail to represent the socio-ecological coupling that produces risk. NBI responds by treating evidence fusion and trustworthiness as first-class

design objects: the orchestrator translates a planning question into an executable workflow with a propagation-based reliability score qualifying the synthesis; GeoResolver binds diagnostics to place and scale [7]; and AGIForecastEngine provides interpretable linear trend baselines enabling forward-looking scenario reasoning without promoting the illusion of high-fidelity long-range forecasting. The architecture thereby aligns with the NbS demand for actions that address societal challenges "effectively and adaptively" [3], and the reliability signalling layer prevents that demand from collapsing into generic narratives by forcing the system to disclose when evidence support is weak or contradictory. NBI is not proposed as a single predictive model, nor as an automated authority that replaces planning judgment. It is proposed as an auditable decision-support language that can stabilize infrastructure-planning workflows under heterogeneous evidence by computing consensus and communicating reliability, while keeping outputs legible as location-bound diagnostics and scenario baselines. Future work should formalize the propagation-based reliability model through systematic evaluation, extend scenario baselines beyond linear trends where warranted by data quality and governance capacity, and integrate official local datasets and sensor-based observations to strengthen accountability in operational deployments. The framework presented in this paper clarifies that NBI is a conservative screening and prioritisation layer: it does not equate hazard detection with risk assessment, and it does not substitute for statutory engineering assessment or emergency authority judgement. This paper has operationalised NBI through an HEVC screening equation, a separate reliability equation, confidence gates and an Eskişehir pilot demonstration.

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Investigation of Geopolymer Solutions for 3D-Printed Sustainable Buildings

A. Z. Kebir[1](✉), X. Thomollari[2], and A. Ivanovs[3]

[1] Yildiz Technical University, 34200 Esenler, Istanbul, Türkiye
zara.kebir@yildiz.edu.tr
[2] Eight Versa, London, UK
[3] Lisäpalvelu Helsinki Oy, Helsinki, Finland

Abstract. This review explores the potential of geopolymers for 3D printing applications, with a focus on construction. The study first examines the prospects of 3D printing technology, highlighting its growth, particularly in housing construction, and the requirements for suitable materials that address current challenges related to climate change and resource scarcity. Modern research indicates that geopolymers are highly suitable alternatives to Portland cement, offering comparable or superior physical and mechanical properties without the need for costly additives. Their environmental advantages include reduced CO_2 emissions, lower energy requirements during manufacturing, and the potential use of secondary raw materials through industrial symbiosis. The review further discusses the enhancement of the reactivity of geopolymer binders through mechanical activation applied to precursors. This method is more economical, efficient, and environmentally friendly compared to calcination, as it requires lower energy consumption and does not involve high temperatures, which reduces the carbon footprint. Additionally, mechanical activation enhances the reactivity of the materials, which can accelerate the curing process and reduce production time. Two generations of geopolymers are examined: metakaolin-based and fly ash-based, with particular attention to the mechanical activation of fly ash and clay minerals, especially kaolinite, which increases strength and enables production without thermal curing. The findings demonstrate that 3D printing technology in construction is expected to expand, and geopolymers based on mechanically activated kaolin are promising materials for this application, highlighting their relevance to sustainable and innovative building technologies.

Keywords: Geopolymers · 3D Printing · Kaolinite · Mechanical Activation · Advanced Composites · Sustainable Buildings

1 Prospects for 3D Printing

Construction 3D printers have appeared on the market relatively recently and are now developing very rapidly, disrupting the conservative construction industry. By reducing material consumption, saving time, minimizing space requirements, and allowing unprecedented geometric freedom, these printers accelerate construction and eliminate

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the human factor, as demonstrated by the case studies reviewed in this article. According to the Grand View Research report [1], the 3D printing market is projected to grow at a cumulative annual rate of 20.8% from 2022 to 2030, with the number of printers in use worldwide increasing from 2.2 million to 21.5 million units.

Below are examples of building and construction projects implemented using 3D printers.

China:	A 10-unit residential building (2015), a 1,100 sq. m mansion (2015), and a 105.91 sq. m farmhouse (Wujiazhuang Village, October 2021) [2–5].
UAE:	A 640 sq. m municipal office (Dubai, 2016–2019) [6–10].
Russia:	A 38 sq. m house (Stupino, Moscow Oblast, 2017) and a 34-unit cottage village of 80 sq. m each (Zelenodolsk District, Republic of Tatarstan, 2022) [6, 11, 12].
USA:	A 32.52 sq. m house (Austin, Texas, 2018); a wind turbine tower (2020); a prefabricated two-bedroom home (Southern California, 2022); a 185.81 sq. m house (Long Island, New York, August 2022); and a social housing project of two single-story houses (63 sq. m each, 2.2 m-high printed walls; La Unión, western Antioquia, Colombia, April 2026) [6, 13–20].
Europe:	A 30 sq. m house (Ravenna, Italy, 2018); a 95 sq. m house (Nantes, France, 2018); a 60 sq. m house (Ravenna, Italy, 2019–2021); an apartment building (380 sq. m, Wallenhausen, Germany, November 2020–April 2021); and a 94 sq. m house (Eindhoven, Netherlands, April 2021) [6, 20–29].
Africa:	A school building (55.74 sq. m, Malawi, June 2021) [30].
Australia:	A recycled plastic house (28 sq. m, currently under production, May 2026) [31].

From the list above, it is evident that 3D printing will become increasingly attractive, as it addresses challenges such as constructing houses in cramped conditions. Traditional housing methods are often too time-consuming and expensive, making homes unaffordable for many people. At the same time, our planet is facing increasing pollution and the progressive depletion of natural resources. 3D printing technology enables houses to be built relatively cheaply and quickly [20, 32, 33]. For instance, Cementos Argos constructed two single-story houses, each with a 63 sq. m floor plan, 3D-printed directly on site in just 16 h over 3 days. According to COBOD, this process is 30% faster than traditional building methods [20]. Similarly, ICON aims to address homelessness by producing small houses that can be 3D-printed in 48 h at a cost of only $10,000 [32]. In addition, this technology helps conserve conventional concrete—where Portland cement is a significant source of CO_2 emissions—and reduces material waste [20].

In the context of research on projects implemented using 3D printing from 2015 to 2026, it can be seen that 3D printing is most often used for the construction of walls. This approach allows for both manual and automated work to be performed simultaneously, saving time and money. For example, the walls of a school with an area of 55.74 sq. m were printed in just 18 h. According to the author [30], such a school will help attract more students and provide solutions for a country facing a shortage of 36,000 classrooms. Filling this deficit using traditional construction methods would take approximately 70 years. Another example is the “Yhnova” house [24, 25], which was part of a social housing project aimed at building affordable, adaptive, and energy-efficient homes in

the shortest possible time and at minimal cost. Printing the 95 sq. m house took 54 h, not including the 4 months that contractors spent installing windows, doors, and roofing. The construction of such a house cost 20% less than an identical house built using traditional methods. Yet another example is the "Gaia" house [21], with an area of 30 sq. m, built in 240 h. This prototype has the potential to serve as a model for constructing homes in poorer countries or regions where housing affordability is a critical issue.

From all of the above, we can conclude that 3D printing is no longer just a theoretical concept, but a practical and achievable solution to modern and future human needs. There are already projects aimed at creating suburban neighborhoods using the same construction principles [12]. It is also clear that in the future, 3D printing will be applied not only to residential buildings [10, 14, 34].

2 Studies on Geopolymers as a Material for 3D Printing

Population growth and ongoing urbanization continue to drive strong demand for cement and concrete, which are key materials for infrastructure and construction. According to the International Energy Agency (IEA) [35], global cement demand in 2026 is estimated at approximately 4.2–4.3 billion tonnes, with long-term projections suggesting an increase to 4.7 billion tonnes by 2050 (~12%). At the same time, alternative scenarios indicate the possibility of demand stabilization or even decline due to the adoption of new construction materials and improvements in resource efficiency.

Against this background, there is growing interest in geopolymer compositions as promising materials for construction and 3D printing. Geopolymer binders are considered a more environmentally friendly alternative to conventional cement, as their production can significantly reduce the carbon footprint while maintaining high mechanical performance and durability [36]. The use of geopolymers offers opportunities for developing a more sustainable construction industry that addresses current challenges related to climate change and resource scarcity.

Table 1 below compares the density and strength of selected printed geopolymer specimens with those of molded specimens.

Table 1. Characterization of printed and molded geopolymer specimens (density and strength).

References	Technology	Density (g/cm^3)	Comp. strength (MPa)		Flex. strength (MPa)	
			7 days	≥ 28 days	7 days	≥ 28 days
[37]	printed	2.0–2.3	22.7–55.2	34.2–95.6	5.9–10.3	8.7–12.6
[38]	mold-cast	N/A	7–15	28–38	2–3	5.5–11.5
	printed	N/A	4–6	27–35	1–2	9.5–11.5
[39]	mold-cast	1.1	N/A	16	N/A	N/A
	printed	0.85	N/A	10	N/A	N/A

Table 2 below summarizes studies that present geopolymers as alternative materials for 3D printing.

Table 2. Studies on geopolymers (GP) used as 3D printing materials.

References	Composition	Printed product
[37]	Fly ash–slag-based GP mixture with silica fume; Fly ash–slag-based GP mixture; Metakaolin–slag-based GP mixture.	Wall element
[39]	Ferro-sialate GP binder (Na/Al = 1).	Prisms (4 × 4 × 16 cm)
[40]	Fly ash–slag-based GP mixture with hemp shives.	–
[41]	Fly ash–slag-based GP mixture.	Small scale objects
[42]	Metakaolin (750 °C)-based and fly ash-based GP.	Small scale objects
[43]	Fly ash–slag-based GP concrete with microencapsulated phase change materials.	–
[44]	Metakaolin (800 °C)-based GP.	Small scale objects
[45]	Metakaolin-based GP with wollastonite and glass fibers.	Radioactive waste cell specimen (d = 35 cm, h = 45 cm)
[46]	Metakaolin-based GP concrete with PP fiber.	–
[47]	Fly ash-based GP mortar with halloysite and metahalloysite (800 °C).	Prisms

Nowadays, geopolymers are classified into five generations [48]. As shown in Table 2, the most extensively studied compositions for 3D printing are metakaolin-based (first-generation) and fly ash-based (second-generation) geopolymer mixtures.

2.1 Mechanical Activation of Fly Ash and Kaolin: A More Sustainable Approach

In this study, a search was also conducted for more sustainable methods for the development of geopolymer formulations suitable for 3D printing. It was found that one such solution could be the mechanical activation of fly ash and kaolin. A comparative analysis of methods for enhancing the physico-mechanical properties of fly ash-based geopolymers was performed [47, 49–56]. Methods of mechanical activation of kaolin clays were also examined [57–60], and an analysis of approaches to improving the physico-mechanical properties of geopolymers based on mechanically activated kaolin was carried out [61–64]. It was concluded that the mechanical activation of fly ash and kaolin represents a more sustainable approach compared to thermal activation, as it involves lower energy consumption and potentially reduced CO_2 emissions. However, its effectiveness depends on the processing conditions, energy source, and the required reactivity of the material.

3 Conclusions and Future Recommendations

This review first considers the prospects for 3D printing development. It was found that this technology holds promise for affordable and emergency housing projects, especially in developing countries, and can be scaled up for larger residential and commercial buildings. Secondly, the use of non-cementitious materials is explored, reflecting the search for new binder systems for 3D printing. The use of geopolymers in this technology shows significant potential, though their properties depend on the precursor and curing conditions. Researchers typically propose tailored recipes based on local raw materials and environmental factors. Based on compressive and flexural strength tests, geopolymer mixtures are considered a viable alternative to cement-based compositions in 3D printing construction. Thirdly, fly ash, granulated blast furnace slag, and calcined kaolin are the most studied precursors for geopolymer formulations used in 3D printing. However, the availability of fly ash is declining as coal-fired power plants are phased out. By 2050, the availability of these materials is expected to decrease by more than half, increasing competition for these by-products. This underscores the importance of studying alternative geopolymers based on clay minerals, which are widely available and can meet the demands of the cement industry. Mechanical activation of clay minerals can also reduce energy consumption and carbon footprint, making geopolymer formulations more sustainable.

It is recommended to develop geopolymer formulations based on mechanically activated kaolin, considering the following parameters:

Viscosity and yield stress: The mixtures should exhibit shear thinning behavior similar to cement pastes. No plateau should be observed when using the Stress-Plateau method, and the Bingham model should show a good linear relationship between shear stress and shear rate. The coefficient of determination (R^2) for different models (Modified Bingham, Stress-Plateau, Herschel-Bulkley, De Kee, and Casson) should be consistent to ensure measurement reliability.

Mechanical properties: The mixtures should be designed to achieve maximum compressive strength by promoting pore filling and matrix densification. In this context, various curing strategies for 3D-printed mortars, including ambient, thermal, moisture-controlled, electrical, and hybrid approaches, should also be considered.

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Data Availability Challenges in Construction to Support Circularity and Decision-Making Processes

Juan Antonio Ferriz-Papi(✉), Vahid Babaveisi, and Angel Jimenez-Aranda

University of Salford, Manchester M5 4WT,, UK
{j.a.ferriz-papi,a.jimenez-aranda}@salford.ac.uk,
Vahid_1110@yahoo.com

Abstract. The construction industry plays a major role in the transition toward a circular economy, yet its progress is constrained by persistent challenges in data availability and quality. Lifecycle-based circularity assessments require detailed information such as material composition, quantities, structural performance, maintenance records and end-of-life scenarios to support accurate decision-making, but this information is often fragmented across stakeholders who operate in isolated digital environments and rely on incomplete or outdated documentation. Legacy buildings add another layer of uncertainty due to poor as-built records and limited material traceability, making it difficult to identify feasible pathways for reuse, recycling and recovery.

This paper presents a PRISMA-based systematic review of peer-reviewed studies from 2020 onwards which aims to examine data-availability barriers specific to construction and their implications for implementing circularity strategies, including material passports, design for disassembly and closed-loop material flows. The analysis identifies recurrent challenges across design, manufacturing, construction, use and end-of-life stages, as well as five key data categories and the stakeholder groups responsible for them. It also synthesizes technical and organizational solutions such as interoperable BIM-based data schemas, standardized digital product passports, digital inventories, IoT-enabled performance monitoring, geospatial material stock mapping, blockchain-supported traceability and collaborative data-sharing platforms. By bringing together current initiatives and best practices, the paper outlines a practical roadmap for overcoming data challenges and supporting more robust circularity practices across the construction sector.

Keywords: construction · circular economy · data availability · traceability · digital product passport · BIM

1 Introduction

The construction sector requires a digital transition shift to support circular economy implementation. Efforts are being taken to support this shift, but it is currently held back by limited data availability across the asset lifecycle. Information on aspects such as material composition, quantities, performance and end-of-life options is scattered across

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organizations and systems, or not structured properly, this way becoming fragmented, inconsistent and difficult to access [1, 2]. Therefore, practitioners often base construction project decisions on incomplete, non-comparable data, and makes it difficult to evaluate circularity on a consistent, evidence-based way and support decision-making processes [2, 3].

Data gaps have evident consequences. Circular strategies such as design for disassembly (DfD), high-value reuse, selective demolition and robust life cycle assessment (LCA) all depend on reliable and interoperable information, but stakeholders involved (e.g. designers, contractors or asset managers) cannot have a full picture of material stocks, flows and performance over time [3]. As a result, it is not easy to identify opportunities to recover value from existing buildings, and circularity solutions tend to remain confined to isolated pilots or high-profile projects rather than influencing day-to-day practice across the sector [2, 4].

The aim of the article is to understand where and why data-availability problems arise along the construction lifecycle, which types of data and stakeholders are most affected and what kinds of digital solutions are being proposed to address them [1, 5]. Through a systematic literature review, it is developed a clear picture of the key data categories, actors and decision points that matter for circular construction. The intended impact is to provide researchers, practitioners and policy-makers with a more concrete map of priority data issues and promising digital solutions, supporting more targeted research agendas and guiding investments in digital infrastructure, as well as indicating more effective regulations and guidance that better support circular practices in the built environment [2, 4].

2 Methodology

This study adopts a systematic literature review following PRISMA 2020 [6] to examine data-availability challenges and digital solutions for the implementation of circular economy strategies in construction. The review protocol specified the research questions, search strategy, eligibility criteria and data-extraction procedures in advance to ensure transparency and reproducibility.

The literature search was conducted in Scopus database due to its broad coverage of peer-reviewed journals and conference proceedings in construction, engineering and environmental fields. The final search string was: “construction” AND “circular economy” AND (“data” OR “data availability”) AND (“challenge” OR “challenges” OR “barrier” OR “barriers”) AND “digital” AND (“solution” OR “solutions”).

Results were limited to English-language scientific articles (journals and conferences) published from 2020 onwards, since preliminary checks found little relevant work before this date. No restrictions were placed on geographical scope or methodological design, whenever the construction sector was explicitly addressed.

A total of 37 records were identified in the search. In a first step, seven papers were excluded because full-text access was not available. For the rest, titles and abstracts were reviewed to exclude publications which were clearly not linked to construction, circular economy or data-related challenges and digital solutions, as well as non-article items (e.g. editorials, short notes). Next, a full-text screening identified those articles

that explicitly focus on construction or the built environment, include circular economy, discuss data-related aspects (availability, quality, interoperability, traceability, monitoring) and address the use of digital technologies. This process yielded a final sample of 22 articles, including primary research and review papers.

For each included study, information was extracted using a structured template covering bibliographic details, study context, challenges per lifecycle stage, data types, stakeholder groups, critical decision points, digital technologies, solutions and limitations for implementation. The extracted descriptions were coded and harmonized to enable cross-comparison across studies. The dataset forms the basis for the synthesis of challenges, data needs, stakeholder roles and solutions in sect. 3.

3 Findings

3.1 Data Availability Challenges

Table 1 presents the main challenges identified for data availability that limit the implementation of circular economy strategies across the construction lifecycle. The meta-analysis developed compares how data gaps happen at different stages of the built asset life cycle. This cross-cutting view highlights that, although the specific issues vary by lifecycle stage, they consistently relate to fragmentation, lack of standardization and limited feedback loops.

Table 1. Main challenges for data availability.

Design
1. Static and geometry-based BIM Models with limited integration of cost, circularity and waste data and weak connectivity between systems [1, 4, 7, 8]; 2. Scarce data on existing buildings and material stocks [4, 5, 8, 9]; 3. Fragmented, non-standardized definition of inventories, passports and circularity indicators, limiting interoperability and comparability [3, 4, 10–12]; 4. Lack of guidance on how to combine structural, energy, environmental and occupancy data, or on which product-level attributes are needed to support future reuse [4, 8, 10–17].
Manufacturing
1. Low digitalization and fragmented records of environmental and lifecycle data across material and product supply chains, and weak integration of manufacturers' internal systems with tracking platforms [5, 8, 9, 11, 13–16, 18]; 2. Incomplete, inconsistent data on material properties, environmental impacts and recovery rates across databases and companies [4, 5, 8, 10, 13–15, 18]; 3. Lack of interoperable standards for product-level circularity and passport data across suppliers and regions [3, 4, 9–12, 15, 16, 18]; 4. Technical and organizational barriers to real-time data capture from production, especially for SMEs [8, 11, 14, 15, 18, 19].

(*continued*)

Table 1. (*continued*)

Construction
1. Fragmented, poorly integrated digital tools on site, with low use of Building Information Modelling (BIM) and poor interoperability between platforms and devices [4, 5, 7–9, 14, 16–21]; 2. Non-standardized and largely manual collection of data on materials, waste, logistics and productivity, with lack of links to BIM and circularity indicators [4, 5, 7–9, 14, 18–23]; 3. Difficulties integrating tracking technologies and digital twins (DT) with BIM to locate and monitor components in real time [4, 8, 12, 14, 16–20]; 4. Scarcity of robust, labelled datasets for AI-based monitoring of progress, quality and construction and demolition waste [4, 9, 12, 14, 16, 19, 22, 23].
Use/maintenance
1. Limited, non-standardized recording of operational data, and weak integration into BIM or inventory systems [3–5, 7, 8, 10, 13–18, 20, 21]; 2. Persistent gaps between predicted and measured performance (e.g. energy, resource use) due to missing in-use data [4, 7, 10, 13–15, 21]; 3. Inefficient feedback loops from facility-management systems to design models and product data [3, 5, 8, 10, 16–18, 20, 21]; 4. Poor component traceability, condition and modifications during use, limiting potential reuse and recovery options [2, 4, 8, 10, 12, 16, 18, 21, 23].
End of life
1. Incomplete, unreliable information on material composition, hazards and recyclability of existing assets [3–5, 9, 10, 13–15, 21, 23]; 2. Lack of structured digital inventories and passports, and limited open data on construction and demolition waste (CDW) composition and recovery options, limiting selective demolition, reuse and recycling at large scale [3–5, 8–10, 12–14, 16, 18, 21, 23]; 3. Weak digital traceability for reclaimed elements, undermining trust and quality assurance [4, 8–10, 12, 16, 18, 21]; 4. Methodological and data gaps for representing alternative end-of-life and circular scenarios in LCA and decision-support tools [4, 5, 8, 10, 13–15, 18].
Whole life cycle
1. Strong fragmentation of data, tools and responsibilities, and a lack of common data models and standards linking product, building and city-level information [1–4, 8, 10–12, 16]; 2. Data quality, completeness and traceability issues that accumulate from early design to end-of-life and reduce confidence in circularity assessments [2, 4, 5, 7–10, 13–16]; 3. Limited longitudinal data and feedback to support learning across projects and assets over time [2–4, 7–10, 14, 16, 18]; 4. Organizational and governance barriers that prevent stakeholders from sharing data and maintaining lifecycle-wide digital records [2–4, 8–10, 12, 16–18].

3.2 Types of Data, Stakeholders and Critical Decision Points for Circularity

This section synthesizes the reviewed studies to clarify which data support circular practices in construction, which stakeholders generate and use them, and when these data become critical for decision-making. The literature shows that circularity depends less on collecting new data than on ensuring that existing information is structured, interoperable, and trustworthy so it can move across organizational boundaries throughout the

asset lifecycle [1–5, 7–10, 12, 16]. Based on the coded fields "Types of data," "Stakeholders," and "Critical decision points," a framework links data categories, actors, and decisions by grouping stakeholders into five roles according to their responsibilities for producing, managing, and using circularity data. Table 2 maps these groups to key data categories and the digital systems used to manage them, highlighting coordination needs to better support circular strategies.

Table 2. Main stakeholder groups, data categories and typical tools and systems.

Stakeholder group	Main data categories	Typical tools and systems
Upstream actors (manufacturers, suppliers, logistics)	Product geometry and technical specs; environmental and circularity data (EPDs, recyclability, LCA); prices and logistics costs; basic traceability data [2–5, 8–10, 12, 16, 18]	ERP/PLM/MES systems; LCA/EPD databases; product data templates; passport/EPD portals; logistics tracking [2–5, 8–10, 12, 16, 18].
Project delivery actors (designers, engineers, contractors, site/BIM managers)	BIM geometry and quantities; design-stage LCA and circularity KPIs; project and waste costs; site productivity and logistics; installed-product traceability [1, 3–5, 7–10, 12–14, 16–21].	BIM authoring tools; CDEs; 4D/5D planning and cost tools; site-management and ERP software; on-site tracking (RFID/ QR/sensors) linked to BIM/DT [4, 5, 7–10, 12, 14, 16–21].
Asset and city actors (owners, facility/asset managers, housing associations, infrastructure operators, municipalities)	Operational and maintenance data (energy, comfort, failures); portfolio-level environmental and circularity metrics; lifecycle costs; building and stock inventories [1–5, 8–10, 12, 14, 16, 18, 21].	CAFM/CMMS; BMS/BEMS; asset- and portfolio-management tools; GIS; digital building logbooks and inventory platforms; dashboards linked to BIM/DT [2–5, 8–10, 12, 14, 16, 18, 21].
Regulatory and governance actors (policymakers, standardisation bodies, certification schemes, auditors)	Regulatory indicators and reporting data; circularity and waste metrics; compliance-oriented traceability and passport information; aggregated performance statistics [2–5, 8–10, 12, 16, 18, 20, 21].	Regulatory and reporting portals; certification/rating systems; standardized data models and code lists (e.g. for BIM, waste, passports) [2–5, 8–10, 12, 16, 18, 21].

(*continued*)

Table 2. (*continued*)

Stakeholder group	Main data categories	Typical tools and systems
Market and innovation actors (platform providers, technology vendors, consultants, researchers)	Integrated views of all data categories to enable analytics, benchmarking and circular business models [2–5, 8–10, 12–14, 16–21].	Circularity and reuse platforms; digital marketplaces; data-integration platforms/data lakes; analytics and AI services; development environments for BIM, DT, inventories and passports [2–5, 8–10, 12–14, 16–21].

The "Critical decision points" highlighted in the reviewed articles show that the value of data for circularity is concentrated in a relatively small number of key moments across the life cycle. These can be grouped into five main clusters:

(i) Early concept and schematic design decisions fix the main spatial, structural and material choices, so access to reliable geometric, environmental and cost data, together with information on reuse and recycling options, is essential to avoid locking in linear solutions [1, 3–5, 7–10, 12–16, 18].
(ii) System and material selection then specifies products and suppliers, where detailed technical data, environmental declarations (EPD), circularity indicators and origin information are needed to compare alternatives and check whether they support disassembly, reuse or high-value recycling [2–5, 7–10, 12–16, 18, 21].
(iii) During construction, planning and site management decisions depend on data about quantities, sequencing, logistics, waste options and on-site monitoring. The degree of integration between BIM, site-management tools and tracking technologies strongly influences how far circular practices can be implemented [4, 5, 7–10, 12, 14, 16–21].
(iv) In the use phase, major refurbishment, retrofitting and maintenance decisions require up-to-date information on component condition, performance, accessibility and potential reuse markets, alongside data on environmental and economic impacts of different interventions [3–5, 7–10, 12–16, 18, 20, 21].
(v) Demolition and deconstruction strategies determine whether buildings become waste streams or material banks. At this stage, high-quality inventories, material passports and data on hazards, recyclability, markets and regulations are needed to plan selective dismantling, reuse and recycling. Otherwise, conventional demolition and low-value recycling remain [2–5, 8–10, 12, 14–16, 18, 21, 23].

These decision points indicate that circularity depends on aligning data and stakeholder responsibilities, rather than trying to capture all possible data continuously.

3.3 Emerging Digital and Organizational Solutions for Circular Data Flows

This section examines how digital and organizational solutions can address data-availability challenges and help embed circular practices in construction, arguing that

progress depends on three complementary layers: (i) information backbones that integrate lifecycle data across actors and stages, (ii) data-capture and traceability technologies that feed these backbones with reliable, timely information, and (iii) governance and standards that make data sharing and interoperability viable in practice. Rather than adding more tools, the priority is to align these layers so that circularity-relevant data are structured, connected, and maintained where they can influence design, construction, operation, and end-of-life decisions. Table 3 outlines main solution types, technologies typically involved in each layer, and their role in enabling circular data flows, improving data availability and usability for circular construction.

Table 3. Digital solutions for circular data flows

Solution layer	Technologies	Main role
Information backbone [1–5, 7–10, 12–14, 16–21]	BIM/CDE; semantic digital twins; digital inventories and building logbooks	Integrate and host lifecycle data across stages and stakeholders
Data capture & traceability [2–5, 8–10, 12–14, 16–21]	IoT/sensors; laser scanning; robotics; material/digital product passports; product circularity data sheets; circular economy platforms	Populate backbone with reliable, real-time and traceability data
Governance & standards [1–5, 7–12, 14–21]	BIM/IFC standards; waste/material codes; LCA schemas; passport standards; data-sharing agreements; procurement clauses; skills and roles	Enable interoperability, trust and sustained data quality

Further analyses can include other practical factors such as implementation conditions, costs organizational readiness and real-world barriers. Progress towards circularity will depend on the co-evolution of digital infrastructures, standards and practices that improve data availability and usability across the construction lifecycle.

4 Conclusions

The review confirms that data availability remains a major challenge for circular construction. Information across the asset lifecycle stages is often scattered, incomplete, and difficult to connect, with particularly large gaps for existing buildings and later lifecycle stages where decisions on reuse, refurbishment, and demolition are made. These conditions limit the ability of designers and practitioners to plan and implement circular strategies beyond isolated pilot projects, even though a range of digital tools (e.g., BIM, CDE, digital twins, inventories and logbooks, IoT monitoring, and product or material passports) already exist and could address many of these gaps if used in a more coordinated way. Their limited impact is mainly due to poor interoperability, fragmented

responsibilities, and weak data governance rather than technological constraints, underscoring the need for shared data models, clearer responsibilities for data management, and stronger alignment between research, practice, and policy so that relevant data are captured and used throughout the facility lifecycle.

The review also has some limitations, as the search was restricted to the Scopus database, a relatively high-level search string, only peer-reviewed journal and conference papers, with 7 papers excluded due to lack of full-text access. Therefore, some studies may have been missed. Future research should therefore broaden databases and document types, deepen full-text and case-based analyses, and empirically test the digital solutions identified here to validate, refine and extend the roadmap for improving data availability in support of circular construction.

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A Machine Learning–Based Hybrid Framework for Multi-Criteria Material Selection

Berfin Yildiz(✉)

Department of Architecture, Bilkent University, Ankara, Turkey
berfin.yildiz@bilkent.edu.tr

Abstract. The increasing impacts of global warming have made energy-efficient design and low-carbon material selection critical challenges in the built environment. Externally insulated composite wall systems involve complex multi-criteria decision-making processes because operational thermal performance is closely related to the embodied carbon associated with material production. This study proposes a hybrid methodology that integrates machine learning (ML) and multi-objective optimization to evaluate material combinations, simultaneously considering both thermal performance and embodied carbon indicators. A dataset was constructed using key design inputs, including insulation material type (mineral wool, glass wool, EPS, XPS, etc.), layer configuration, insulation thickness, climate zone, and wall surface area. Based on these inputs, a multi-output regression model was developed to predict both thermal performance and embodied carbon. Replacing computationally expensive simulations with ML-based predictions significantly accelerates the exploration of larger design spaces. The predicted performance indicators were then integrated into a multi-criteria evaluation framework that also incorporates acoustic insulation performance as an additional decision parameter. The results indicate that aerated autoclaved concrete (AAC) combined with glass wool provides balanced performance in several climatic conditions. The findings demonstrate that ML-based decision-support models can substantially improve computational efficiency while enabling broader exploration of sustainable material alternatives. However, the proposed framework relies on the scope and quality of the available dataset and considers a limited set of wall assemblies and insulation materials. Despite these limitations, the methodology provides a scalable approach for supporting early-stage material selection in performance-driven architectural design.

Keywords: Machine learning · Embodied carbon · Thermal performance · Multi-objective optimization · Sustainable material selection

1 Introduction

The construction sector is responsible for a substantial share of global energy consumption and greenhouse gas emissions. The environmental impacts associated with buildings occur not only during the operational phase but also throughout the life cycle of construction materials, including production, transportation, and installation. For this reason, sustainable building design increasingly requires a holistic perspective that considers both

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operational energy and embodied impacts. Building energy consumption is influenced by multiple parameters, including climatic conditions, occupant behavior, mechanical systems, and architectural design decisions. Among these factors, the building envelope plays a crucial role in regulating heat transfer between indoor and outdoor environments, thereby significantly influencing overall building energy efficiency. Externally insulated composite wall systems enable a wide range of design alternatives through variations in material types, insulation thicknesses, and layer configurations. However, this diversity also increases the number of design alternatives, making insulation material selection a complex multi-criteria decision problem.

Traditionally, evaluating such alternatives relies on physics-based simulations and detailed thermal calculations. Performing energy analyses for each alternative separately can be computationally intensive, particularly during early design stages. As a result, designers often evaluate only a limited set of alternatives, which may lead to overlooking optimal solutions. Recent advances in machine learning (ML) offer promising opportunities to address these limitations. ML models can learn complex relationships from data and rapidly predict building performance, enabling efficient exploration of large design spaces. In this context, the present study proposes a machine-learning-based hybrid material selection model for externally insulated composite wall systems. The model simultaneously predicts thermal performance and embodied emissions, integrating these outputs into a multi-objective decision-making framework that also considers acoustic insulation performance. By combining ML-based prediction with multi-criteria evaluation, the proposed approach aims to provide a computationally efficient decision-support method.

2 Related Works

2.1 Machine Learning in Performance Prediction

In recent years, data-driven models have been used to predict building energy consumption, thermal performance indicators, and environmental impacts by learning complex relationships between material properties, climatic conditions, and design parameters. Compared with traditional physics-based simulations, ML models can significantly reduce computational time while enabling rapid exploration of large design spaces. Several studies have demonstrated the potential of ML approaches for predicting building energy performance and lifecycle impacts. Sharif et al. [1] developed artificial neural network models capable of predicting energy consumption, lifecycle cost, and environmental indicators of building systems. Similarly, Abdolvand et al. [2] proposed an integrated ML framework for estimating building energy loads together with embodied energy metrics. Chen et al. [3] introduced a BIM-based prediction system that evaluates thermal performance and embodied energy values of insulation materials. Zhou et al. [4] investigated the relationship between operational and embodied carbon in energy-efficient buildings, showing that the relative importance of embodied carbon increases as operational energy demand decreases. These studies demonstrate that ML-based surrogate models can provide reliable predictions while significantly reducing the computational burden of detailed simulations. Despite these advances, most ML-based studies primarily focus on predicting energy consumption or thermal performance indicators,

while other performance aspects relevant to construction material selection are rarely incorporated into the modeling framework.

2.2 Performance Criteria in Material Selection

Establishing performance criteria is crucial for evaluating materials in building envelope design. Early studies focused primarily on improving operational energy efficiency by optimizing insulation materials and wall assemblies. Roberts et al. [5] compared different insulation materials in terms of thermal performance and environmental impact, highlighting the critical role of material selection in reducing building energy demand. With increasing attention to sustainable construction, lifecycle assessment (LCA) indicators have also been incorporated into evaluation frameworks for insulation materials. Carreras et al. [6, 7] proposed approaches that simultaneously evaluate the lifecycle environmental impacts and the economic performance of building envelope components. These studies emphasize the importance of considering embodied energy and carbon emissions associated with material production and transportation in addition to operational energy performance.

In addition to thermal and environmental considerations, acoustic insulation represents another important performance aspect in building envelope design. The composition and configuration of wall assemblies significantly influence sound transmission and indoor acoustic comfort [8, 9]. Fibrous insulation materials, such as mineral wool and glass wool, have been widely studied for their combined thermal and acoustic properties [10].

In particular, acoustic performance is rarely incorporated into multi-objective decision-making processes. To address this gap, the present study proposes a machine-learning–based hybrid framework for selecting insulation materials in externally insulated composite wall systems. The proposed model predicts thermal performance and embodied indicators using a multi-output ML model, while acoustic insulation performance is incorporated as an additional criterion in the subsequent multi-objective evaluation process. This approach enables a more comprehensive assessment of insulation materials while significantly reducing computational costs associated with traditional simulation-based methods.

3 Methodology

This study proposes a hybrid framework that integrates ML–based performance prediction with a multi-objective material selection approach for externally insulated composite wall systems. The framework aims to support the selection of insulation materials by simultaneously considering thermal performance, embodied carbon emissions, and acoustic insulation performance. The overall workflow of the proposed methodology can be summarized as follows: (i) preparation of the material dataset, (ii) training of the multi-output machine learning model, (iii) prediction of thermal and environmental performance indicators, and (iv) multi-objective evaluation and material selection. This hybrid approach allows rapid evaluation of a large number of design alternatives while maintaining a comprehensive performance assessment. The system boundaries of

the study are defined at the building envelope component level, focusing on material production, transport, and assembly stages (cradle-to-site). Operational energy effects are indirectly represented through thermal performance indicators, while end-of-life scenarios are not included.

3.1 Dataset and Input Parameters

The dataset was generated based on combinations of commonly used materials in externally insulated composite wall systems. The wall assembly consists of interior plaster, a structural wall layer, an insulation layer, and exterior plaster. As structural wall materials, conventional brick and autoclaved aerated concrete (AAC) blocks were considered. For the insulation layer, four widely used materials were evaluated: expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool, and glass wool. Material properties are obtained from manufacturer technical datasheets and Environmental Product Declarations (EPDs), while environmental indicators are derived from lifecycle assessment datasets. The input parameters used in the ML model are shown in Table 1.

Table 1. Input features

Feature	Unit	Description	Source
Material Property			
Density	kg/m^3	bulk density of insulation material	technical sheets, EPD
Thermal conductivity	W/mK	thermal conductivity coefficient	technical sheets, EPD
Recycled content	%	proportion of recycled material content	technical sheets, EPD
Additive content	%	percentage of binder or additives	technical sheets, EPD
Design Variable			
Thickness	mm	thickness of material layer	design parameter
Mass per area	kg/m^2	calculated material mass per square meter	design parameter
Window to wall ratio	%	ratio of total window area to exterior wall area	design parameter
Logistics			
Transport emission factor	$kgCO_2e/(ton{\cdot}km)$	emission factor for material transport	EPD

(*continued*)

Table 1. (*continued*)

Feature	Unit	Description	Source
Transport distance	km	distance between manufacturer and construction site	location parameter
Climate			
Heating degree days (HDD)	°C·day	indicator of heating demand	
Cooling degree days (CDD)	°C·day	indicator of cooling demand	
Climate zone	categorical	Climate classification	TS825

3.2 ML Model for Performance Prediction

A machine–learning–based surrogate model is developed to predict key performance indicators for insulation materials. The model is designed as a multi-output regression framework capable of simultaneously predicting thermal performance and embodied environmental impact indicators. In this study, the Extreme Gradient Boosting (XGB) [11] algorithm was selected as the primary regression model due to its high predictive performance, robustness to nonlinear relationships, and effectiveness when working with relatively small to medium-sized datasets. XGB is an ensemble learning method based on gradient boosting decision trees, which iteratively improves prediction accuracy by combining multiple weak learners into a strong predictive model. Compared with traditional machine learning algorithms, XGB offers several advantages, including regularization mechanisms that reduce overfitting, efficient handling of heterogeneous input features, and strong predictive performance in regression problems. The model outputs include: thermal performance indicators (thermal resistance, R-value) and global warming potential (GWP). The ML model learns the relationships between the input variables and the performance indicators using the prepared dataset.

3.3 Multi-Objective Material Selection

After obtaining the predicted thermal and environmental performance indicators, a multi-objective evaluation process is used to identify suitable materials. In addition, acoustic performance was incorporated as an additional decision criterion in the optimization process. Acoustic insulation performance was quantified using weighted sound reduction index values and empirical correlations with material density, thickness, and porosity [10]. For composite wall assemblies, the overall acoustic performance was approximated using mass-law-based formulations and layer-wise contribution models, enabling consistent integration into the multi-objective evaluation framework. To determine optimal trade-offs between these competing objectives, the Non-dominated Sorting Genetic

Algorithm (NSGA) III was employed. NSGA-III is a widely used evolutionary optimization algorithm for solving multi-objective problems and generating Pareto-optimal solutions. The algorithm iteratively evolves a population of candidate solutions using selection, crossover, and mutation operators, ranking them by Pareto dominance and crowding distance. Pareto-based analysis is used to determine optimal trade-offs between thermal efficiency and embodied energy while ensuring adequate acoustic performance. These solutions provide designers with a range of alternative insulation configurations rather than a single optimal solution, allowing flexible decision-making depending on project priorities.

4 Results

4.1 Machine Learning Model Performance

The predictive performance of the proposed machine learning model was evaluated using the Extreme Gradient Boosting (XGBoost) algorithm. To assess the model's accuracy, predicted values were compared with the reference dataset using scatter plots of predicted versus actual values. R^2 represents the proportion of variance in the target variable that can be explained by the input features and is therefore commonly used to evaluate the predictive performance of regression models. The R^2 value ranges from 0 to 1, with higher values indicating better model performance. Figure 1 illustrates the prediction performance of the XGBoost model for each output variable. The predicted–actual comparison for thermal performance (Fig. 1 - *left*) shows a strong linear relationship between predicted and actual values, indicating that the model captures the relationships among insulation thickness, thermal conductivity, and other material properties. R^2 values measured as 0.695. The high concentration of points around the diagonal line suggests that the model provides reliable predictions for thermal resistance values.

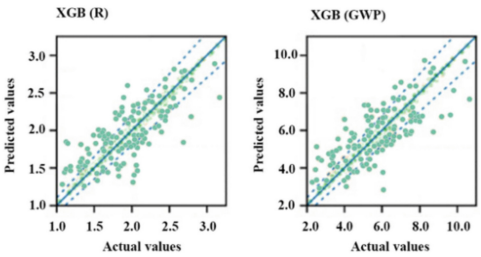


Fig. 1. Comparison between predicted and actual values of R and GWP.

Similarly, the results for global warming potential (Fig. 1 - *right*) show good agreement between predicted and actual values. The model effectively captures the influence of manufacturing energy, material density, and transport distance on lifecycle carbon emissions. The relevant R^2 value for this model is 0.711. Overall, the XGBoost model demonstrates strong predictive performance across the outputs, indicating that the selected input parameters adequately capture the factors influencing both thermal performance and embodied environmental impacts.

4.2 Multi-Objective Evaluation

Following the performance prediction stage, the predicted indicators were integrated into the multi-objective evaluation framework. The optimization model simultaneously considered three performance criteria: thermal performance (R-value), embodied environmental impacts (GWP), and acoustic insulation performance. A Pareto-based analysis was conducted to identify optimal trade-offs between these criteria (Fig. 2). Insulation configurations with higher thermal resistance generally exhibit increased embodied emissions due to greater material use or higher manufacturing energy requirements. Conversely, materials with lower environmental impacts may provide moderate thermal performance. When acoustic performance is incorporated as an additional decision parameter, fibrous insulation materials such as mineral wool and glass wool frequently appear among the Pareto-optimal solutions due to their balanced thermal and acoustic properties. In particular, systems combining autoclaved aerated concrete (AAC) structural walls with glass wool insulation demonstrate a favorable balance between relatively low embodied energy values and acceptable thermal performance. AAC exhibits lower density and thermal conductivity, contributing to improved thermal resistance, whereas conventional brick provides higher thermal mass.

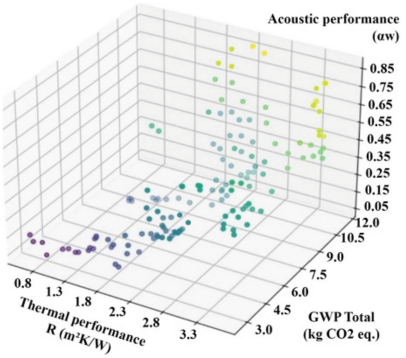


Fig. 2. 3-D Pareto-optimal solution space

5 Conclusion and Discussion

This study presented an ML–based hybrid framework for selecting insulation materials in externally insulated composite wall systems. The proposed approach integrates a multi-output XGBoost model for predicting thermal performance and embodied environmental impacts with a multi-objective evaluation process that also considers acoustic insulation performance. The results demonstrate that the machine learning model provides reliable predictions for thermal resistance and global warming potential (GWP). The strong agreement between predicted and actual values indicates that the selected input parameters effectively represent the relationships between material properties, design variables, and lifecycle environmental impacts. It should be noted that, while

thermal resistance is widely used as the primary thermal performance indicator due to its early-stage design and regulatory compliance, it does not fully capture dynamic thermal behavior, such as heat storage capacity and time-lag effects. Future extensions of the model could incorporate parameters such as heat capacity and thermal diffusivity to better capture time-dependent heat transfer behavior. The proposed framework is designed as a generalizable decision support model. Regulatory requirements can be included as external constraints depending on the geographical context.

The multi-objective analysis reveals the balance between thermal performance and embodied environmental impacts, highlighting the importance of considering multiple criteria in material selection. It should be noted that the dataset is limited to commonly used traditional insulation materials. Future studies aim to include alternatives with low carbon footprints, such as bio-based or recycled materials. Future research may also explore the application of alternative machine learning algorithms, such as random forests, support vector regression, and neural networks, and compare their predictive performance with that of the XGBoost model. Such comparisons could further improve the robustness and generalizability of machine learning–based material selection frameworks.

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Integrating Circular Economy Indicators into BIM: Insights from a Stakeholder Survey

Vanessa Tavares[1(✉)], Ana Rute Costa[2], Camila Cervantes[3], Hafize Büşra Bostancı[4], Ihab Al-Qazzaz[5], Joana Maia[6], José Gonçalves[7], Kenza Belkhiri[8], Marco Delli Paoli[9], Marta Maria Sesana[10], Mehmet Emiroglu[11], Milena Rajić[12], Moses Itanola[13], Pelin Sertyeşilışık[14], Sefa Guntepe[15], and Viorel Ungureanu[8]

[1] BUILT CoLAB, Rua do Campo Alegre 760, 4150-171 Porto, Portugal
vanessa.tavares@builtcolab.pt
[2] Lancaster School of Architecture, Lancaster University, Lancaster LA14YW, UK
[3] Department of Civil Engineering, ISISE, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal
[4] Department of Architecture, Hitit University, Çorum, Turkey
[5] Shiite Endowment Office, Baghdad, Iraq
[6] CONSTRUCT, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
[7] MARE Marine and Environmental Sciences Centre, ARNET Aquatic Research Network Associate Laboratory, NOVA School of Science and Technology, NOVA University Lisbon, Largo da Torre, 2829-516 Caparica, Portugal
[8] Politehnica University Timisoara, Faculty of Civil Engineering, 2 Piata Victoriei, 300006 Timisoara, Romania
[9] Department of Planning, Design, Technology of Architecture, Sapienza University of Rome, Via Flaminia, 72, 00196 Rome, Italy
[10] Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), Università degli Studi di Brescia, Via Branze, 43, 25123 Brescia, Italy
[11] Sakarya University, Esentepe Campus, Kemalpaşa Mahallesi, Üniversite Caddesi, 54187 Serdivan/Sakarya, Turkey
[12] University of Niš, Faculty of Mechanical Engineering, Aleksandra Medvedova 14, 18000 Niš, Serbia
[13] Belfast School of Architecture and the Built Environment, Ulster University, Ulster University Campus, York St, Belfast BT15 1ED, UK
[14] Construction Department, Afyon Kocatepe University, Afyon Vocational School, Afyonkarahisar 03200, Turkey
[15] Fibrobeton Inc, Kavacık Dist., Ertürk Str., No:11/Z-1 Beykoz, Istanbul, Turkey

Abstract. Advancing circularity in the built environment requires harmonised methods for defining and managing Circular Economy (CE) indicators throughout the project lifecycle. This paper presents a structured survey-based investigation into current practices, data requirements, and digital workflows associated with CE assessment in construction. It also provides a survey-based investigation of stakeholder perspectives, data requirements, and digital workflows related to the integration of CE indicators into Building Information Modelling (BIM) environments. The survey engaged stakeholders from Portugal, Serbia, and Romania

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to examine barriers, data structures, and reporting needs associated with CE–BIM integration. The findings show that CE indicators are mainly assessed during early design stages, while lifecycle-wide BIM integration remains limited due to fragmented data structures, insufficient standardisation, and unclear regulatory guidance. Unlike studies focused mainly on technical BIM functionalities, this paper provides stakeholder-driven insights and policy-oriented recommendations to support future harmonisation of CE–BIM practices and lifecycle data management.

Keywords: Building Information Modelling (BIM) · Circular Economy (CE) indicators · data requirements · life cycle assessment · stakeholders survey

1 Introduction

The transition toward a Circular Economy (CE) in the built environment is essential to reduce resource depletion, waste generation, and lifecycle carbon emissions, particularly given the construction sector's significant environmental footprint [1]. Recent EU-wide assessments further emphasise this urgency, showing that buildings account for around 36% of total greenhouse gas emissions in the European Union and highlighting the need for robust, harmonised lifecycle data to support decarbonisation strategies [2]. In this context, Building Information Modelling (BIM) has emerged as a promising digital approach for improving data management, traceability, and coordination across the building lifecycle. However, despite growing interest in CE–BIM integration, the implementation of consistent CE indicators within BIM workflows remains fragmented and insufficiently standardised across the AECO sector. Based on a structured stakeholder survey across the construction value chain, this paper investigates stakeholder perspectives, data needs, and implementation barriers related to the integration of CE indicators into Building Information Modelling (BIM) environments and discusses policy-oriented recommendations to support more harmonised CE data practices.

BIM is a collaborative digital methodology that supports the planning, design, construction, and management of buildings through intelligent nD models enriched with structured lifecycle data. By enabling multidisciplinary coordination, improved interoperability, and better decision-making, BIM enhances efficiency, cost control, and sustainability. As a combination of policies, processes, and technologies, it represents a major shift in the AEC industry by improving collaboration, reducing errors, and supporting integrated information management [3].

Furthermore, in CE research, indicators are diverse quantitative or semi-quantitative measures used for benchmarking, decision support, performance monitoring, and communication, varying by scale and purpose. While many indicators focus on material preservation - especially recycling - circularity in the built environment also depends on durability, adaptability, reusability, and design for disassembly [4–6]. Building-specific indicators are particularly valuable for guiding design decisions, but studies highlight ongoing fragmentation in assessment frameworks and limited integration of energy and emissions metrics [7, 8]. Tools such as material passports and BIM-based lifecycle assessment models can help operationalise these indicators by improving data availability and traceability [9]. In this context, the transition from a linear to a CE represents

a fundamental shift in resource and waste management, requiring more integrated and lifecycle-oriented approaches to material and building information management.

In the traditional linear model, resources are extracted, transformed into products, and eventually discarded at the end of their useful life, often resulting in significant environmental impacts and resource depletion. In contrast, the CE aims to extend the lifecycle of materials and products through strategies such as reuse, repair, and recycling, thereby reducing waste generation and improving resource efficiency. This approach promotes a more sustainable and environmentally responsible system of production and consumption [6, 7].

BIM plays an important role in supporting this transition within the construction sector. By enabling collaborative digital workflows and integrating virtual design with project delivery processes, BIM can improve material planning, reduce design errors, and enhance coordination among project stakeholders. These capabilities contribute to more efficient material use and reduced construction waste through improved visualisation, clash detection, and planning [10, 11]. Although BIM adoption has grown globally alongside CE initiatives, research indicates that its specific applications for supporting circular strategies across the entire lifecycle of assets remain underexplored. Further research is needed to better understand how BIM can facilitate lifecycle-based circularity practices and strengthen resource efficiency in construction and asset management [10, 12]. Previous studies have focused on linking BIM to custom external databases that contain the CE indicator data required for assessment. More recent studies have explored the integration of CE indicators information within the BIM environment through semantic enrichment using a data dictionary in the buildingSMART Data Dictionary (bSDD). This approach leverages BIM's potential for information management and enables BIM to function as a central data repository throughout the project life cycle [13]. To this end, this study aims to explore country-specific BIM-CE synergy by focusing on the stakeholder perspectives. By conducting an exploratory approach, this study compares the CE indicators requirements for the BIM environment from the data obtained from three countries, Portugal, Serbia, and Romania, and presents the constraints for CE adoption and BIM's potential to accelerate the shift.

2 Materials and Methods

This research examined stakeholder perspectives and current practices related to the integration of CE indicators into BIM environments by analysing stakeholder data needs, workflows, and implementation barriers. An international survey was conducted in multiple languages (Portuguese, Italian, English, Turkish, Serbian, and Romanian) to capture diverse perspectives on CE–BIM integration. The online questionnaire consisted of 31 questions across five sections addressing respondent profiles, stakeholder roles, expectations and constraints related to CE-BIM integration, and the incorporation of CE indicators into BIM workflows. Targeting professionals across the AECO value chain – including designers, engineers, contractors, policymakers, and digital solution providers – the survey collected quantitative data via a five-point Likert scale, as well as multiple-choice and open-ended responses.

Although responses were collected internationally, only Portugal, Romania, and Serbia were considered at this stage, due to a relevant number of responses, with 31, 34,

and 19 respondents, respectively. The data were analysed using descriptive statistics, cross-tabulation, and thematic analysis to identify trends in CE–BIM maturity, stakeholder needs, and key implementation barriers, which informed the development of a policy-oriented framework for the harmonised integration of CE indicators within BIM environments. Although the survey is international, this study focuses on Portugal, Romania, and Serbia due to higher response rates. The results are exploratory and not fully representative of the European AECO sector. Differences in sample size and national BIM and CE maturity may affect comparability. Future research should include more countries and stakeholder groups for broader analysis.

3 Results and Discussion

Most respondents were aged 35–44 (46%), male (62%), and held either a university (54%) or postgraduate degree (56%). The majority had over 10 years of experience in the AECO sector (74%) and worked primarily in architectural design (36%) or engineering consultancy firms (31%). BIM use was mainly at a basic level (viewer or simple model use) (34%) or intermediate level (modelling and coordination) (36%), while the use of CE strategies was typically intermediate (occasional) (46%) or basic (rare) (24%). The ranking of the relevance (from very relevant to not relevant) of various CE indicators to their practice is represented in Fig. 1. Overall, the comparison indicates that while all three countries recognise the importance of CE indicators, Portugal and Serbia display clearer prioritisation patterns, whereas Romania reflects a more heterogeneous perspective. These differences may be associated with variations in policy frameworks, digital maturity, and industry awareness related to CE-BIM integration across the studied contexts.

In Portugal, respondents rated material circularity (e.g., circularity score/MCI), recyclable/recycled content, and reusable content as highly relevant indicators, with a large share of responses concentrated in the "very relevant" and "relevant" categories. Waste-related metrics and durability indicators also received moderate-to-high relevance ratings, suggesting that Portuguese stakeholders prioritise indicators linked to resource efficiency and lifecycle performance. In contrast, indicators such as hazardous materials, toxicity-related metrics, and material traceability were more frequently evaluated as only somewhat or slightly relevant, indicating lower prioritisation in current BIM-based workflows. These findings suggest that the Portuguese AECO sector is particularly focused on the potential for material recovery and lifecycle optimisation as core components of CE implementation.

Responders in Romania show a more distributed response pattern across the relevance scale, indicating a less consolidated perception of CE indicators within BIM processes. Several indicators, including material circularity, reusable content, and waste metrics, received mixed evaluations ranging from "relevant" to "slightly relevant," reflecting varying levels of awareness or implementation of maturity. However, indicators such as design for disassembly, durability/service life, and resource-efficiency strategies are relatively more relevant than other categories, highlighting the growing recognition of lifecycle-oriented design approaches.

In Serbia, the results reveal a stronger concentration of responses in the "very relevant" and "relevant" categories across most indicators, particularly for material circularity, recycled content, and waste metrics. This suggests a relatively strong alignment between CE objectives and BIM data needs among Serbian stakeholders.

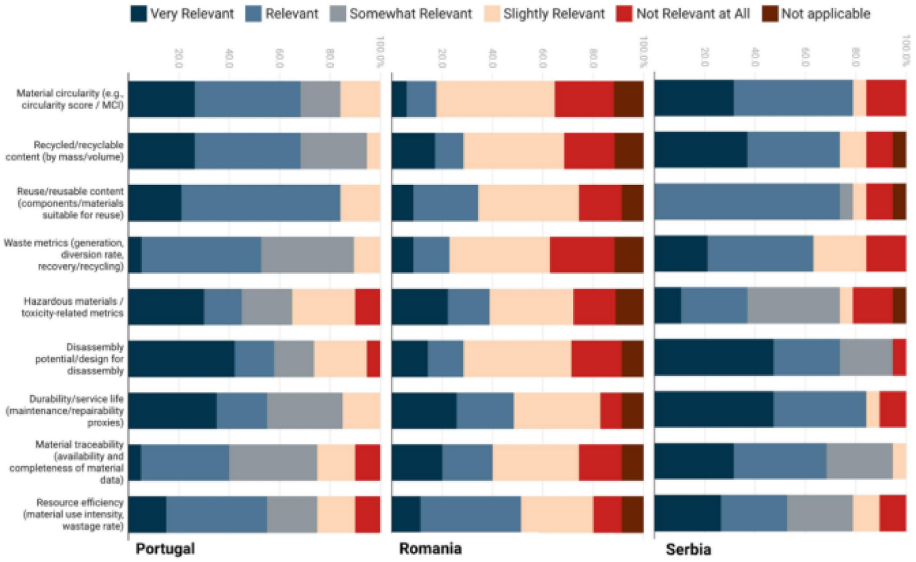


Fig. 1. Relevance of CE indicators to the work of respondents.

CE indicators are most frequently assessed using BIM during the Concept & Early Design and Production & Construction stages, indicating that BIM is primarily applied to support design decisions, material planning, and construction coordination, as seen in Fig. 2. Indicators such as material circularity, recycled content, and resource efficiency are therefore more commonly evaluated in the earlier project phases. In contrast, considerably fewer assessments occur during Use, Operation & Maintenance and End-of-Life, suggesting that BIM is still rarely used to support lifecycle-based circular management, including durability monitoring, disassembly planning, or material recovery.

In Portugal, the results indicate that CE indicators are predominantly assessed during the Concept & Early Design stage, particularly for indicators related to material circularity, recycled content, and resource efficiency. The Production & Construction stage also shows some use of BIM for evaluating indicators such as waste generation and hazardous materials, reflecting BIM's role in construction planning and coordination. However, assessments during Use, Operation & Maintenance and End-of-Life remain relatively limited, particularly for indicators such as disassembly potential, durability, and material traceability. This pattern suggests that while circular considerations are increasingly introduced during design, BIM-supported lifecycle monitoring and end-of-life planning are still not widely integrated into professional practice.

In Romania, CE indicators appear to be assessed more consistently across multiple lifecycle stages compared with the other countries. Both Concept & Early Design

and Production & Construction stages show strong representation for most indicators, including material circularity, reuse potential, waste metrics, and resource efficiency. Additionally, Romania displays comparatively higher levels of assessment during the Use, Operation & Maintenance stage, particularly for durability, service life, and material traceability, indicating a growing awareness of lifecycle-based circular management. Although End-of-Life assessments remain less frequent, the results suggest a relatively higher maturity in integrating CE considerations within BIM workflows.

In Serbia, the assessment of CE indicators using BIM is generally less frequent and more uneven across lifecycle stages. While some evaluations occur during Concept & Early Design, particularly for indicators related to recycled content and material circularity, the overall distribution suggests limited systematic integration within BIM processes. Assessments during Production & Construction and Use & Operation stages are comparatively lower, and the figure shows a higher proportion of responses associated with End-of-Life or Not Applicable categories, especially for indicators such as disassembly potential and hazardous materials. This pattern suggests that BIM adoption for CE evaluation remains at an early stage, with significant opportunities to strengthen lifecycle data integration and circular performance assessment.

Among the three countries, Romania shows the most balanced distribution of assessments across lifecycle stages, Portugal demonstrates moderate integration mainly concentrated in early phases, and Serbia presents lower levels of BIM-supported CE assessment and a higher proportion of responses indicating that indicators are not yet applied.

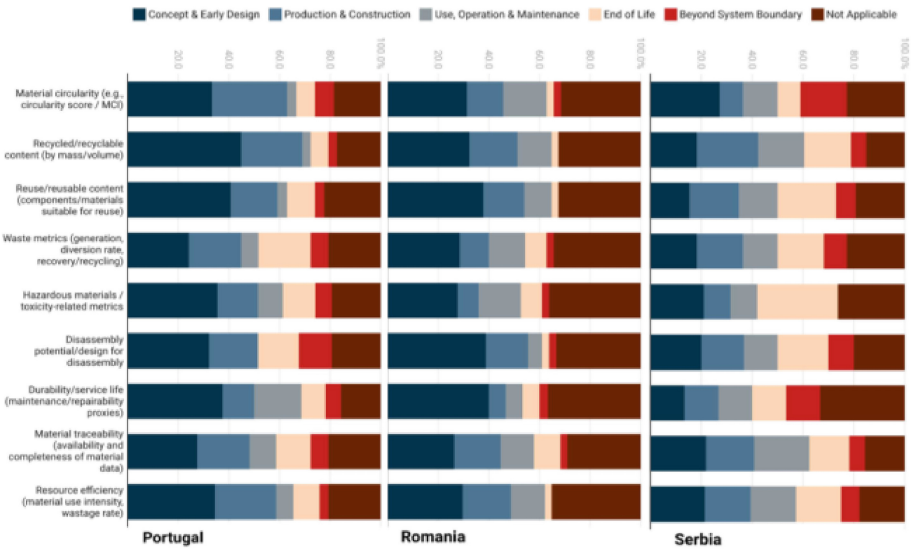


Fig. 2. Stages at which CE indicators are assessed using BIM.

Table 1 maps the key constraints affecting CE adoption onto the BIM capabilities that can most directly address them. It should be noted that these correspondences are

not arbitrary: they emerge from the survey findings, in which stakeholders identified both the barriers they face and the BIM functionalities they consider most relevant to their work. The rationale for each link is therefore grounded in the empirical data and further supported by the existing literature.

Table 1. Top 5 constraints in CE adoption and contribution to CE goals**.**

Constraints in CE adoption	Expected BIM contribution to CE goals – rationale
Lack of skills	Resource and cost optimisation through 4D/5D BIM: 4D scheduling and 5D cost modelling enable non-specialist stakeholders to visualise material flows and lifecycle costs, reducing the impact of skill gaps on CE-informed decision-making.
Cost constraints / Lack of reliable data	Reduction of rework through clash detection: BIM-based collision detection minimises costly on-site errors and supports more accurate quantity take-offs, thereby reducing material waste and associated costs.
Unclear regulatory guidance	Waste reduction through improved planning: BIM enables detailed simulation of construction sequences and material use, supporting compliance-oriented waste management plans even in contexts with fragmented regulatory frameworks.
Lack of standardised BIM data structures	Material quantity accuracy: structured BIM object libraries and IFC-based data schemas improve the consistency and comparability of material data, laying the groundwork for CE indicator reporting.
Lack of (inter)national CE indicator definitions	Material/product data management (EPDs, certificates, etc.) and support for material reuse and recycling: BIM can host and link EPD records, material passports, and circularity certificates, enabling traceability even in the absence of unified indicator definitions.

Moreover, as stakeholder perceptions indicate that BIM is primarily used during the early design stage, strengthening BIM use is needed to support a lifecycle-oriented approach to foster circular transition. This can be achieved by developing a comprehensive policy framework that not only bridges synergies among lifecycle stages but also encourages BIM's contribution to CE constraints. Therefore, future work, based on these findings, is a policy-oriented framework that can be developed to support harmonised CE data practices and promote scalable CE-BIM integration across projects and governance levels. The European Commission [2] identifies three key policy domains, such as improving operational energy performance, accelerating low-carbon material adoption, and enhancing circularity, all of which depend on accessible and structured building-level data. To this end, the policy framework to accelerate CE-BIM integration

through various lifecycle stages directly supports these priorities by enabling traceable, verifiable and interoperable CE-indicator datasets.

4 Conclusion and Final Remarks

This study investigated stakeholder practices, data requirements, and implementation barriers related to CE indicator integration into BIM environments by analysing stakeholder practices, data requirements, and implementation barriers across the AECO sector. The survey results reveal that, although stakeholders recognise the importance of CE indicators, particularly durability, recyclability, reusability, and material circularity, their systematic use in BIM workflows remains limited, often occurring only when required by specific project demands or regulations. The findings also show notable differences among the analysed countries, with Portugal and Serbia demonstrating clearer prioritisation of CE indicators, while Romania reflects more heterogeneous perceptions. Furthermore, the results highlight that CE indicators are predominantly assessed during the concept and early design stages, where BIM is most frequently used to support material selection and design decisions. In contrast, the application of BIM for circularity monitoring during operation, maintenance, and end-of-life stages remains relatively underdeveloped, indicating a gap in lifecycle-wide CE data integration.

Overall, the study confirms that BIM has strong potential to support the operationalisation of CE indicators. However, this potential can only be fully realised through improved data standardisation, interoperability, and governance frameworks. The stakeholder feedback emphasises the need for harmonised data structures, better integration of material information (e.g., material passports and digital building logbooks), and clearer regulatory guidance to ensure consistent CE monitoring across project phases. Based on these insights, the paper highlights the need for a policy-oriented framework to support scalable CE-BIM integration through lifecycle stages, across projects and governance levels. By aligning digital construction practices with CE objectives, such frameworks can support public authorities, industry organisations, and standardisation bodies in strengthening lifecycle data management and accelerating the transition toward a more circular, resource-efficient, and climate-neutral built environment.

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Towards Circular Architecture. The Role of Digital Twin for the Quantification and Valorization of Waste Management

Emma Nivesse[1,2], Isabelle De Smet[1], Nicolas Youssef[2], David Laplume[1], and Sesil Koutra[1(✉)]

[1] Faculty of Architecture and Urban Planning, University of Mons, Mons, Belgium
sesil.koutra@umons.ac.be
[2] Junia, Université Catholique de Lille, LITL, F-59000 Lille, France

Abstract. As a key urban innovation and a cornerstone of sustainable initiatives, Digital Twins (DT) serve as enabling instruments for data-informed, evidence-based transitions, connecting the social, ecological, and spatial dimensions of urban transitions, aligning with European ambitions ranging from promoting energy efficiency to the 2050 decarbonization roadmap. Moving from linear to circular design models, the study fosters adaptive solutions for developing dynamic, learning-oriented circular approaches to construction waste management. Along with a scientific and replicable decision-support tool, the study promotes closed-loop systems in spatial transformations and stark contrasts to the traditional economic models of "take-make-dispose" technocratic solutions and architectural conceptions. The research develops a systematic review of tools for both building-level renovation and district-scale regeneration, mapping reusable resources, quantifying waste, and reducing new material extraction. The research will conclude by determining its applicability in site-specific locations and complex environments through evaluations of the impacts of design interventions and the promotion of mutual understanding of its utility. By bridging the gaps in technical modeling, the collaborative DT processes will leverage sustainability and co-develop and test actionable insights in real-time settings, not only as technological demonstrators but also as participatory instruments for inclusive urban transformations.

Keywords: Circular Economy · Digital Twin · Architecture · Waste management · Decision-support tool

1 Introduction

Construction is one of the major contributors to global waste, accounting for more than 30% of worldwide generation, over 40% of resource use, and 25% of global waste, leading to unsustainable models and emerging alarming situations amid complex, growing environmental challenges. Integrating efficient waste management practices is pivotal to advancing sustainable practices in the construction sector. The built environment is responsible for more than 40% of raw material extraction, and more than one- third of this extraction occurs within European borders [1].

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Moving from traditional models of "take-make-dispose" models towards green transformative shifts and reuse, recycling, and circular models seems imperative to face challenges related to natural depletion, energy consumption, or soil artificialization due to massive urbanization pressures [2]. Proposed by Ellen MacArthur Foundation [3] as a catalyst for the reduction of the building carbon footprint, while promoting efficient strategies for cost, and resources' optimized use [4], Circular Economy (CE) has been increasingly studied as a promising and sustainable concept as opposed to the linear approaches [5], whereas its potential applications in various processes of life cycle (production, consumption, distribution), and its principles of material recycling, and reuse are commonly acknowledged, being closely aligned with the United Nations Sustainable Development Goals (SDGs) in an integrated and transformative framework and promote innovative design strategies supporting resource reutilization and realignment and sustainability. In recent years, the concept of circularity has gained rising scientific and policy interest with the adoption of the First Circular Action Plan in 2019, and continued being institutionalized through European engagements, as the new Circular Economy Action (CEAP) (2020), or Green Deal towards the 2050 decarbonization pathway ([6, 7]). In fact, the transition from 'linear' to 'circular' strategies poses a range of new challenges for designers, requiring the acquisition of specific knowledge, resources, and management skills, as well as the development of novel methods, that operate within closed-loop flows and consider the entire project lifecycle.

Recent research, e.g. ([5, 8]), has been conducted to conceptualize circular design and identify knowledge gaps in construction standards, and still, developments are in an infant stage with significant technological uncertainty. Current trends and standalone and siloed tools have been developed to support circular design and the required skills for designers, with limited, nevertheless, empirical investigation and case-study evidence [9], which have led to fragmented practices and communication inability due to the absence of unified, clarified policy structures or misinterpretations, creating a lack of effectiveness. The study aims to bridge learning outcomes on standardized grounds and promote digitalized tools for practitioners of cleaner production with standardized ontologies and common language, guiding decision-making processes towards greener and resilient practices by exploring the 'digital twinning' strengths and potential in environmental engagements, and restructuring the narrative of current construction models and their disastrous environmental effects.

Circular economy is an umbrella term that encompasses synthetic processes and relevant principles for the use and reuse of materials, operating at different scales of implementation. The concept draws on interdisciplinary roadmaps documented in grey and scientific literature that combine diverse viewpoints from industrial and academic stakeholders. Some of them describe the concept in single conceptualized frameworks, whereas others explore the interconnectivity of its dimensions in more holistic view - points of a "restorative", resilient, and long-lasting architectural and urban design and an instrument for sustainable development practices ([9, 10]).

Construction-intensive activities intensify soil artificialization, leading to major contributions to environmental degradation through excessive waste management and exacerbating serious ecological imbalances. To understand the distribution of the circular economy in scientific research, a selected sample of 1,597 scientific publications from

the Lens.org database was analyzed. To focus the results on the circular economy and related topics, these publications were selected based on the occurrence of the keywords "circular economy" and "architecture". The sample publications were chosen based on their publication year, from 2010 to 2026, because of their increasing mention in the literature since the 2010s ([11, 12]). To specify the sample, a field of study was chosen: waste management, engineering, circular economy, and architecture. To ensure comprehensive cluster outcomes, a minimum benchmark of five (5) occurrences was set. Figure 1 shows clusters in different colors, with node sizes representing keyword co- occurrence and lines representing affinity between them.

The circular economy is linked to many topics through scientific research. Its scope of application is broad and continues to expand. The co-occurrence of keywords in scientific research indicates that research density is higher around circular economy, sustainability, waste management, life cycle analysis, and recycling. The connections between keywords reveal links across disciplines, and the distribution of the cluster demonstrates the movement of scientific research. The main concepts emerging from this cluster are Building Information Modeling (BIM), digital twins, blockchain, and Industry 4.0 with weaker connections between architecture and this cluster.

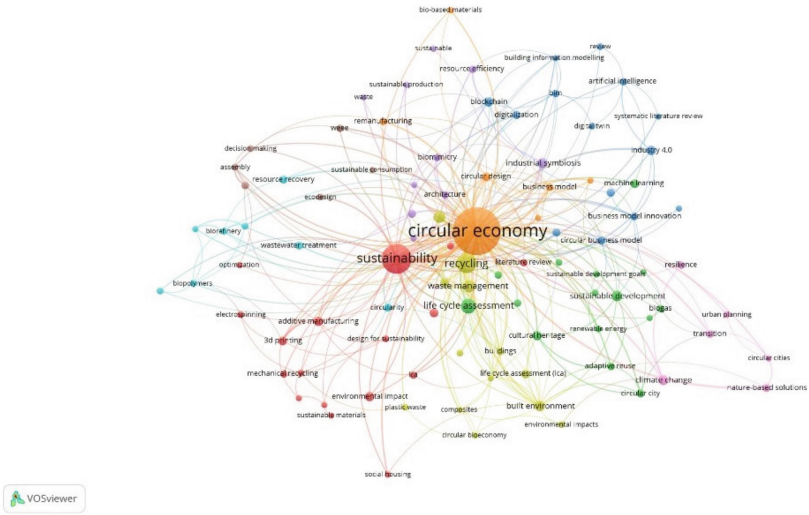


Fig. 1. Bibliometric analysis from Lens.org database, of the scientific research about circular economy and architecture in Europe from 2010 to 2026.

2 Tools. Addressing Gaps and Challenges

To support and enable circular design, a range of tools and methods has been identified and documented in the grey and academic literature; a systematic literature roadmap is provided in this section to identify innovations and relevant gaps. From the same lens, recent research on the conceptualization of the circular economy has systematically

identified significant gaps arising from the lack of unified approaches, leading to misalignments, misunderstandings, and misinterpretations ([13, 14]). Most studies address the transferability of knowledge and common agreements across different methods and tools, and neglect the social implications, behavioral adaptations, and consumer-centric lifestyles, adopting systemic views of a circular mindset, while others focus on waste management and demolition waste [15].

The study revealed complementary difficulties in adapting "design personas," the need for innovative collaboration schemes and relevant competencies, and the need to assess and anticipate plausible environmental impacts and societal adoption challenges in advance. Digital highways synchronize data bidirectionally and bridge data and interoperability gaps on "what-if" scenarios, translating simulation insights into real-world applications in connected ecosystems. Kozminska [17] et al. explored architectural cases in circular design processes, by highlighting innovative standards and the need for interdisciplinarity due to the perplexing nature of stakeholders, emphasizing the role of architects as 'orchestrators' of the process as pivotal to coherent designs

Waste recovery takes place at various levels, depending on the possibility; it starts with prevention, followed by reuse, recycling, and energy recovery. Considering the **project lifecycle criteria** each tool offers a different approach to waste management categorized into nine criteria: tracking, quantifying, mapping, advising, modeling, interconnecting, analyzing, managing, and preventing (Table 1).

Table 1. Objective of the tool for waste management and circular economy in the construction industry

Tool objective	Description
Track	Waste flow tracking
Quantify	Waste quantification and inventory creation
Map	Location of deposits, waste recovery operators and materials
Advise	Inform stakeholders about methods for recovering construction waste
Model	Integrate construction waste into a 3D model
Interconnect	Facilitate exchange between stakeholders about suitable and easily accessible reusable materials
Analyze	Construction data, including its life cycle, performance at the scale of material and building
Manage	Management of construction waste on site, facilitating waste collection
Prevent	Prediction and anticipation of construction waste to reduce its quantity

Existing tools for waste management in the construction industry can be organized with these objectives to expose their roles in the recovery process. The study of a sample of 10 tools that are more often used or mentioned in the construction industry seems to demonstrate their broad scope.

Table 2. Sample of 10 tools used in the recovery of waste in the construction industry

Tools	Track	Quantify	Map	Ad-vise	Model	Intercon-nect	Analyze	Manage	Prevent
Track waste	X	X							
BAMB Materials Passports	X								
TOTEM					X		X		X
DEMOCLES						X		X	X
SimaPro							X		
VALOBIM		X	X						
RREUSE				X					
Opalis						X			
Level(s)							X		
OpenLCA							X		

Table 2 shows a disparity in the purposes of the tools in existing literature, presented with fragmented regard. Each of them is generally part of a post-production waste approach, seeking to manage what happens to waste, while only few of them target the first stage of recovery: prevention, as the case of TOTEM (Belgium) that analyzes the life cycle of a project from the design phase. Version 2020 of the method behind TOTEM was used in the study of Lam et al. (2022) [18].

At first glance, the industry appears well-equipped with tools and methods, but stakeholders face complex, too numerous, and siloed tools. As they are often costly, difficult to use, and time-consuming, it has become difficult for contractors and architects to incorporate them into their thinking. Furthermore, these tools are mainly intended for large-scale projects and large-scale companies. Along with the development of circular economy strategies, digitalization has been identified in diverse studies as an enabler of these practices, yet it is characterized by a significant lack of theoretical or technical background, a fragmented approach, and limited synergies that hinder the feasibility of circular models.

The concept of Digital Twin (DT) dates back to 2002, when industrial designers at the University of Michigan introduced it as a virtual representation of physical assets, aimed at design optimization, the integration of circular standards, and real-time monitoring and material flow [19]. It has progressively emerged as a key enabling technology that addresses design complexities in decision-making processes and is a promising strategy for reducing costs, facilitating innovation, and supporting the green transition, considering the combined information from multiple sources and scales in real-time ecosystems to improve efficiency and time savingsWhen combined with BIM, it enables material and knowledge flows throughout construction and waste management, facilitating the dynamics of automated processes in real-time ecosystems of architectural projects. In

several endeavors and exemplary cases, DT enabled architectural performance through the evaluation of waste volumes and quality, the identification of reuse scenarios aligned with customer preferences, and the distribution of resources, exploring the operational option of DT integration to advance circular economic practices [20]. Despite the multiple assets on DT use, multiple barriers hinder the lack of transparency and traceability with fragmented and underused data and the need for intersections among different sectors, including the barriers of advanced skills and relevant training [21].

3 Discussion

Moving from linear to circular architectural conceptualizations fosters multilevel innovation and adaptive solutions in real-time ecosystems by optimizing time, costs, and resource use and distribution. In this study, a systematic review of existing tools for construction and demolition waste identified significant gaps in communication and collaboration, and the need for more inclusive designs that promote closed-loop systems and holistic support mechanisms, by adding new knowledge to the existing literature.

Moreover, each tool has advantages but also disadvantages that can hinder the development of waste recovery. These drawbacks result in tools that are time-consuming, costly and sometimes expensive, difficult to learn, difficult to apply in the field, often requiring high-performance equipment, and lacking educational value and awareness. BIM-related tools are developing, but small companies do not systematically model their projects, which can be an obstacle to the use of waste recovery software. As an example, some tools are developing into application, to facilitate their use in site to the most stakeholders as possible (for example the tools ValoDépôt, BatiTri, Cycle Zero in France). Developing these types of tools could promote waste recovery among stakeholders who find it difficult to implement, such as small construction companies.

Other factors come into play in waste recovery, such as the location of construction sites and their proximity to sorting and storage facilities, as well as the size of the sites, which, when too small, does not promote waste recovery because of the low rentability for the companies.

4 Perspectives and Future Work

Digital advancements the conceptualization, design, and implementation of architectural projects optimize visualization, data generation, and the development of synergies throughout the project lifecycle, thereby improving communication skills and collaborative schemes among the involved stakeholders. In the next steps of the study, to meet research objectives, empirical studies on benchmarking approaches (France and Belgium) will be conducted to provide avenues for further investigation that emerge from the current discussion. Empirical evidence will be collected towards an in-depth understanding of the DT ecosystem to demonstrate its feasibility and constraints in real-time architectural projects of different scales.. This will help reveal the potential of digitalization as well as its limitations related to technical patterns, participation instruments, and learning processes.

It seems relevant to consider key stakeholders and self-builders such as small construction companies, small design offices, and even, for example, individuals wishing to build and recycle their waste, who also have a role to play in the recovery of construction waste at their scale. The next phase of the study aims to develop a tool that best addresses the existing drawbacks, evaluating the possibilities and limitations of a comprehensive, holistic tool, such as a digital twin or a simpler and more accessible tool for the stakeholders concerned. While considering that these different tools will not be geared towards the same types of projects or stakeholders.

Various tools could be implemented, such as educational sheets for construction workers and self-builders, training sessions for construction companies and their staff, or applications that are easy to bring to the construction site and simpler to use. Waste recovery should target transport-related waste such as packaging, implementation-related waste such as losses, cuttings, and cleaning inherent to the construction site, and demolition and building dismantling waste.

Even though efficient tools exist today, there is a real gap between the birth of innovation and its adoption. Companies do not easily position themselves as leaders but prefer to follow what has already been done. This creates a gap between the creation of a tool and its application. In addition, project size comes into consideration, as tools are less often used in smaller projects.

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An Automated BIM-LCA Framework to Environmental Decision-Making in the Structural Design

Danielle Freitas(✉) and Helena Gervásio

ISISE, University of Coimbra, Coimbra, Portugal
danielle.freitas@uc.pt

Abstract. Climate change challenges the construction sector to develop solutions that balance functional performance with reduced environmental impact. Despite growing interest in sustainability during the design phase, its integration into project workflows remains limited, largely due to the difficulties of linking environmental information to digital models, such as interoperability constraints, risks of data loss, and the time-consuming nature of traditional impact assessment processes. Therefore, this study proposes an approach that integrates Life Cycle Assessment (LCA) with Building Information Modelling (BIM), applied to steel and composite structures. Through an application designed to generate parametrized structural models, designers can define materials and attributes that already include embedded LCA data, allowing immediate access to environmental indicators. The tool supports BIM model exportation with detailed 3D geometry and LCA values, providing quantity take-off and impact analyses directly within the BIM platforms. The results show significant improvements in modelling speed, information automation, and decision-making support, contributing to a more efficient, integrated, and sustainability-oriented design process.

Keywords: Life Cycle Assessment · BIM · Steel and Composite Structures · Sustainable Design · Digital Workflows

1 Introduction

The construction industry is widely recognized as one of the largest contributors to natural resource consumption and greenhouse gas emissions. The sector is responsible for approximately 37% of global CO_2 emissions related to energy and industrial processes, with building construction and materials manufacturing accounting for approximately 11% of this total [1]. Within this context, steel and composite construction offers important advantages such as faster execution, architectural flexibility, and high steel recycling rates [2–5]. However, these benefits do not eliminate their environmental burden, as steel production is highly energy-intensive and concentrates a substantial share of carbon emissions in the early stages of a building's life cycle, before the operational phase begins [3, 6].

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In response, it is essential to integrate sustainability and efficiency into the design and planning stages of civil construction. Digital technologies, such BIM, offer a promising approach, as they allow decisions to be anticipated and alternatives to be evaluated in the early phases of the project [7–10]. One of the main advantages of BIM is its ability to assign detailed parameters to each element of the model, which allows for additional analyses related to costs, energy performance, and environmental impacts.

LCA approach is considered one of the most robust and widely recognized methods for quantifying the environmental impacts of products and building systems [11]. The application of LCA in BIM models has been recommended because it enables analyses that are closer to the project reality and promotes greater integration among design disciplines [12]. In addition, from a practical perspective, designers still face difficulties in creating parametric families and managing reliable technical data, both of which require considerable time and specialized knowledge [13]. As a result, issues related to model detail, data standardization, software compatibility, and the correct linkage of environmental parameters continue to limit the effective integration of BIM and LCA [14–16].

Given this scenario, this study proposes a solution for the automated generation of BIM elements for steel and composite structural systems, integrating construction and environmental data to support LCA at early design stages. The approach is intended to reduce modeling time, standardize information, and enable the incorporation of sustainability criteria into design project workflows.

2 Materials and Methods

The proposed approach consists of developing a tool to automate the generation of steel and composite building systems organized as macrocomponents. The methodology is structured as an integrated workflow comprising three complementary components: a web-based interface for user input and plugin distribution, an LCA calculation procedure, and a developed Revit plugin.

The overall workflow of the web-based interface system is illustrated in Fig. 1, which is structured into three main parts: **(i)** input data, **(ii)** assessment of embodied life cycle impacts, and **(iii)** outputs.

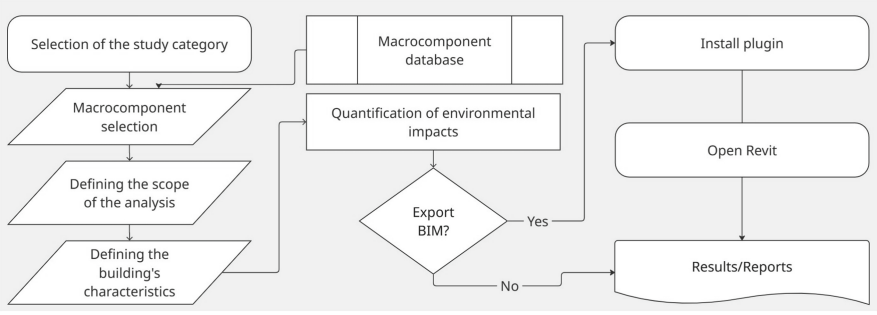


Fig. 1. Workflow tool.

Users can perform an LCA either at the level of an individual building component or at the level of building type, including single-family, multi-family, institutional, industrial, and commercial buildings. After selecting the assessment mode by category, the user selects the specific macrocomponent to be analyzed. The macrocomponents were classified using a UniFormat system [17] and their detailed structure is shown in Fig. 2.

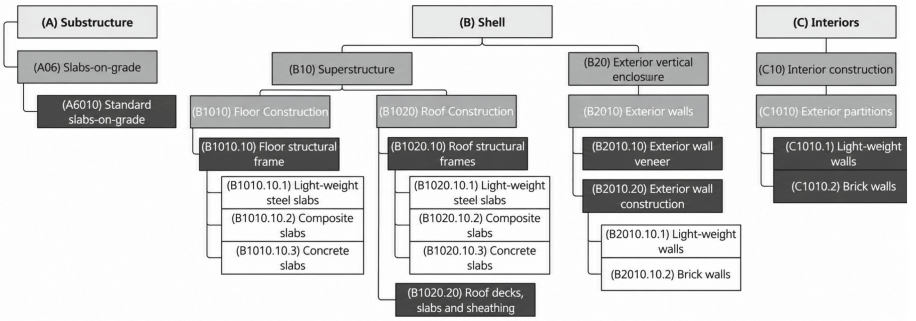


Fig. 2. Macrocomponent classification.

The user can define a set of attributes, including constituent materials, insulation type and thickness, and the LCA scenarios to be considered. The insulation materials available for selection include rock wool, expanded polystyrene (EPS), extruded polystyrene (XPS), glass wool, polyurethane (PUR), polyethylene (PE), cork, wood fibers, and external thermal insulation composite systems (ETICS). Materials are retrieved from a previously structured library that assigns to each material its density, recycling rate (RR%), and potential end-of-life scenarios. This material library is linked to an Excel-based LCA databse developed from Life Cycle Inventory (LCI) datasets derived from the Ecoinvent database [18], following the methodological framework described by [19]. The database was structured to include the environmental data required for the materials and life-cycle modules considered in the study, in accordance with ISO 14040:2006, ISO 14044:2006, EN 15804:2012, and EN 15978:2011.

Based on the input data, the tool performs the LCA calculation using a predefined functional unit of **1 m^2 of macrocomponent over a 50-year lifespan**. The generated results allow the user to visualize not only climate change impacts in **kg CO_2-equivalent**, but also additional environmental indicators relevant to a broader assessment, such as environmental impacts (GWP-total, GWP-fossil, etc), resource use (PERE, PERT, etc), output flows, and waste categories (HWD, NHWD and RWD). Once the calculations are completed, the application presents the results according to the selected scope, allowing the user to consider **A1–A3** (product stage), **C1–C4 and D** (end-of-life and beyond system boundary), or the full **A–D life cycle**.

Based on these inputs, the plugin reads the information provided through the web-based interface and automatically instantiates the corresponding Revit family, assigning the parameters to the model. The plugin was developed using Dynamo visual programming and enables the instant generation of parametric families based on a set of previously developed parametric families representing the building components considered

in the study. These families were created and structured based on technical datasheets of real national construction systems, ensuring that their geometry, material composition, and constructive characteristics reflect representative solutions used in practice. They were then organized according to the classification adopted in the methodology, allowing the plugin to associate each selected macrocomponent with its corresponding geometry, material composition, and relevant attributes for subsequent LCA processing.

3 Results

The proposed tool was tested using all macrocomponents implemented in the system, considering a functional unit of 1 m^2 for each element. Figure 3 illustrates the different types of macrocomponents available within the tool.

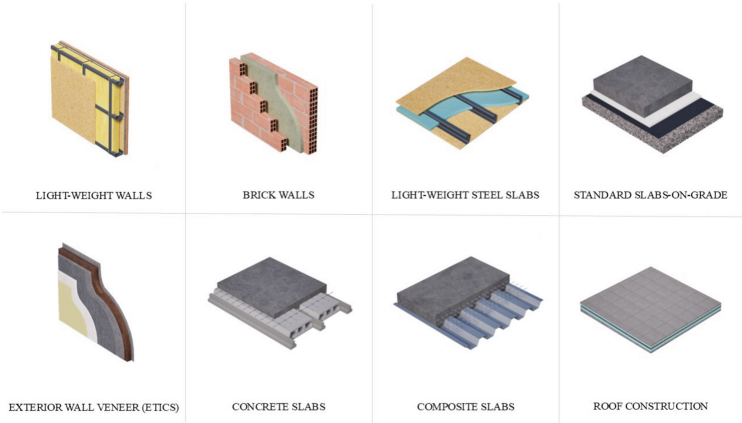


Fig. 3. Macrocomponents types.

The validation process involved selecting the various insulation materials available in the database, as well as defining the corresponding construction parameters and LCA scopes. Figure 4 presents the web-based interface where the selection and definition of macro-component characteristics are performed.

After calculation, the tool enables an "Export BIM" function that allows users to download the "BuildingsLCA" plugin [20]. The generated macrocomponents can be imported into Revit as RFA format, already containing both construction attributes and the associated environmental results.

These data are embedded as family type parameters, enabling direct access, filtering, and quantification within the BIM environment. Once loaded into Revit, each macro-component provides a detailed geometric representation, its constituent materials, and the corresponding LCA indicators, allowing designers to model the element while simultaneously accessing the environmental information integrated into the BIM object. The values are presented as parameters within the Model Properties of each macrocomponent family and are organized alphabetically according to the LCA scope analyzed to facilitate interpretation by designers. Using these parameters, it becomes possible to develop

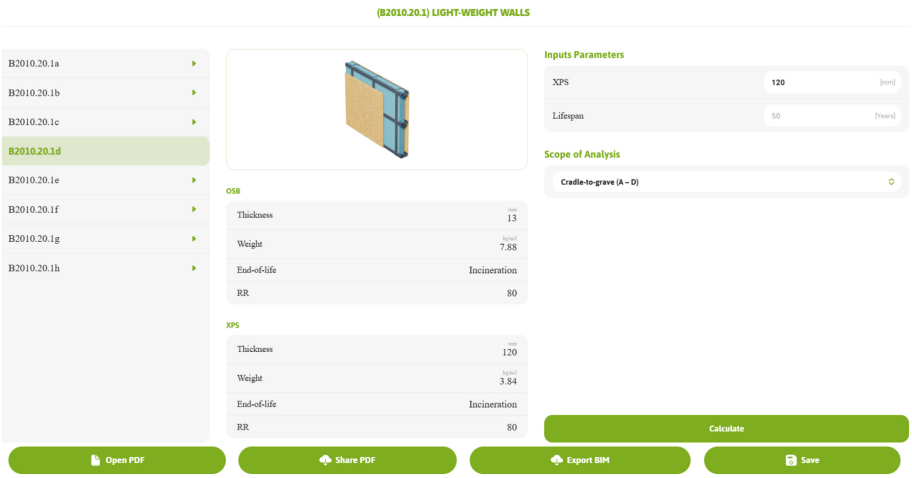


Fig. 4. Definition of the attributes of macrocomponent B2010.20.1 for LCA calculation.

BIM projects and, at the end of the design process, obtain their overall environmental impact.

The LCA values obtained using the tool were validated by comparing the automated results generated by the tool with the reference calculations previously developed in the Excel-based LCA database. For the validation, the same material quantities, input parameters, life-cycle scenarios, and environmental indicators were considered. The consistency between the two sets of results confirmed that the tool correctly retrieves the environmental data, associates them with the corresponding material quantities, and applies the calculation procedure as intended.

4 Discussion

The proposed workflow was tested across all macrocomponents included in the tool. In all cases, the tool successfully generated the corresponding BIM objects, performed the LCA calculations according to the selected scope, and exported the components to Revit with both construction and environmental parameters embedded.

However, due to the complexity of these construction systems, the slab and roof macrocomponents are exported as Structural Framing Beam families, which must be applied within Revit's Structural Framing System. This approach is necessary because the floor categories in Revit do not allow the insertion of detailed steel structural elements, being limited to a 2D graphical representation. Similarly, macrocomponents representing lightweight construction solutions are exported as Curtain Wall system families.

Despite these implementation constraints, the results indicate that the developed tool substantially reduces the time required for the initial generation of detailed parametric families. In the tested workflow, the comparison focused specifically on the initial modelling stage, namely the creation and parameterization of complex BIM families. While the manual creation of a family of this type, level of detail and data information can take

several hours, the automated workflow enables the equivalent family to be generated and imported into Revit in approximately 10 min, representing a significant reduction in initial modelling time. This comparison refers specifically to the generation of the parametric family and does not include subsequent operations such as model verification, re-importing after design changes, or minor manual adjustments.

5 Conclusions

Considering the limited expertise of many designers in developing detailed BIM objects, as well as the challenges associated with integrating BIM elements with LCA studies, the developed tool presents a promising solution. The system allows for the parametric configuration of different types of building systems. Exporting enables the creation of families applicable to Revit architectural models with a significant level of detail, including 3D steel structures, which facilitates visualization, coordination, and quantity takeoff.

Obtaining LCA results for building elements is simple and immediate. The parameters are integrated into the properties of the created families, allowing environmental analyses to be carried out more efficiently and directly within the BIM environment. Therefore, beyond improving modeling efficiency, the solution also can promote circular economy principles into early design stages by embedding material, recyclability, and end-of-life information into BIM objects. This is particularly relevant for steel construction, where recycling, disassembly, and component reuse represent important pathways to reduce embodied environmental impacts.

Despite its flexibility and user-friendly workflow, some limitations remain. Whenever it is necessary to add a new material or change the thickness of the thermal insulation, the configuration must be recreated in the tool and exported again to Revit. Furthermore, converting macrocomponents into Revit system families rather than loadable conventional families proved to be a practical solution, but may introduce additional complexity for designers mainly due to the inherent restrictions of the software when handling this type of family. Nevertheless, the tool also demonstrated its ability to significantly reduce the time required to model complex families.

For future work, it is considered relevant to explore extending the system to automatically generate complete building models with predefined dimensions and construction elements, instead of exporting only individual objects. Additionally, integrating graphical visualizations and comparative LCA reports directly into the tool interface would facilitate interpretation and decision-making. Expanding the system to include other classification systems and integrating it with national or regional environmental databases adapted to different countries would further enhance the tool's potential for international applicability.

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UID/PRR2/04029/2025, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020.

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Mapping Agentic AI Integration in the Circular Built Environment: A Systematic LoD Maturity Model

Nilüfer Kızılkaya[1(✉)], Hafize Büşra Bostancı[2], Ali Murat Tanyer[1,3], Temitope Omotayo[4], and Abisola Muftau[4]

[1] Department of Architecture, Middle East Technical University, Ankara, Türkiye
knilufer@metu.edu.tr
[2] Department of Architecture, Hitit University, Çorum, Türkiye
[3] Center for the Built Environment and Design (MATPUM), Middle East Technical University, Ankara, Türkiye
[4] School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds, UK

Abstract. The circular built environment is characterized by dynamic building lifecycles, driven by heterogeneous material flows, iterative operational conditions, and multiple stakeholders. These requirements closely align with advances in emerging agentic Artificial Intelligence (AI) systems, enabling autonomous task decomposition, multi-tool reasoning, and feedback-driven adaptation. Despite rapid progress in autonomous multi-agent systems and digital twin (DT) intelligence, the integration of agentic AI into the circular built environment remains in its early stages. This study proposes an automated Level of Development (LoD) maturity assessment framework to evaluate the readiness of agentic AI workflows for circular construction applications. A two-phase systematic literature review was conducted to construct three research domains representing (1) agentic AI in the built environment, (2) circular construction, and (3) BIM/DT-based lifecycle digitalization. Cross-domain mapping revealed strong coupling between circularity and AI-enabled BIM/DT research, a developing trend between agentic AI and digitalization, and a limited intersection between agentic AI and circularity. The maturity classifications were mapped onto a LoD 100–500 scale, ranging from single-agent systems to autonomous frameworks. Initial maturity scores were generated using a large language model based on a six-dimensional (D1–D6) agentic maturity rubric covering agency structure, tool integration, reasoning depth, adaptivity, autonomy, and environmental data resolution. The outputs were assessed using an LLM-assisted consistency-checking procedure across rubric dimensions. The proposed framework provides a scalable approach to assess the readiness of agentic AI systems for the development of autonomous circular construction workflows

Keywords: Agentic Artificial Intelligence · Circular Construction · Multi-Agent Systems · BIM · Digital Twins · Maturity Assessment

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1 Introduction

Generative artificial intelligence (GenAI), particularly through large language models (LLMs), has initiated a new phase of transformation in architecture, engineering, and construction (AEC) through access to information, decision support, and workflow automation [1]. This transformation signifies not only the emergence of new tools but also the restructuring of knowledge-intensive, multi-stakeholder, and interdisciplinary construction processes. However, the use of these technologies in AEC carries significant limitations. Productions that are insufficiently grounded in domain knowledge can lead to problems such as hallucinations, contextual disconnection, unjustified decision-making, and outdated information [2]. These problems become more critical in BIM-based environments where structured data, classification systems, standards, and lifecycle-based decision approaches require co-working.

Research into reliable GenAI in the AEC is increasingly evolving toward retrieval-augmented generation (RAG) and agentic AI. RAG aims to improve factual accuracy and contextual appropriateness by grounding LLM outputs in external, validated information sources for information retrieval [3–5]. For the execution of more complex workflows, agentic AI enables task breakdown, tool handling, multi-agent coordination, memory management, and structured reasoning [1, 6]. Despite this progress, the use of agentic AI in circular construction remains limited and fragmented. Effective management of such processes requires AI systems capable of interpreting different data sources, evaluating decision alternatives, and operating adaptively throughout the lifecycle. BIM-DTs stand out as fundamental digital infrastructure that stores and updates circular construction information such as reuse of building components, material composition, component history, performance data, operational status, and end-of-life management [7].

Current research in agentic AI is concentrated in operational monitoring, DT simulation, smart building management, and auditing [8–10]. This shows a significant research gap that requires higher-level digital intelligence capable of interpreting data in context and translating it into lifecycle decisions. This study aims to address this gap by providing a Level of Development (LoD)-based maturity framework to evaluate the current maturity of agentic AI in circular construction. For this, the interdependencies among the agentic AI, circular economy, and BIM fields were examined. The results map the binary relationships between the fields and reinterpret the LoD concept through a maturity lens, enabling the co-reading of BIM data reliability and AI autonomy.

2 Method

The research has a threefold methodology including pairwise domain mapping across key research fields, LoD-based maturity classification through a lifecycle approach, and agentic AI maturity evaluation using a multidimensional rubric. The pairwise domain literature mapping is based on comparing dependencies of three emerging research domains within the built environment: (1) Agentic AI in construction; (2) Circular construction systems; (3) BIM-based digitalization using DTs. The proposed maturity evaluation framework, applied to the literature findings, aims to identify (i) how agentic AI systems interact with digital building data infrastructures and (ii) to what extent they support circular construction workflows.

2.1 Pairwise Domain Mapping

A pairwise domain mapping strategy was employed to analyze the relationships between the three domains: (1) Circular construction and AI-enabled BIM-DT; (2) Agentic AI and BIM-DT**;** and (3) Agentic AI and circular construction. These domains were compared to examine research developments across different levels of AI autonomy in digital infrastructure. The study first evaluated the two dominant pairwise relationships observed in the literature. The relationship between agentic AI and circular construction was found to be very limited and therefore treated as exploratory.

The literature dataset was compiled through systematic searches of Scopus, Web of Science, and IEEE Xplore. After screening and eligibility assessment, two subsets were extracted from the literature corpus. The first subset included 25 studies [11–35] where circular construction practices are operationalized through lifecycle digitalization platforms. These studies mainly focus on material tracking, lifecycle assessment, material passports, reuse planning, and deconstruction modeling. The second subset comprised 12 publications [36–47] focusing on autonomous AI systems characterized by capabilities of task decomposition, tool integration, multi-agent coordination, and adaptive reasoning.

This study reinterpreted the traditional geometric-based LoD scale as a dual maturity framework, linking BIM data reliability and agentic AI autonomy within circular construction workflows [48]. The Agentic LoD (ALoD) categories were interpreted across three circular construction lifecycle phases: early concept and design estimation, coordination and deconstruction planning, and autonomous material recovery and end-of-life management. The lifecycle phases are defined in Fig. 1 based on the combined progression of BIM data reliability and AI autonomy, and the maturity levels used to classify the review results are summarised in Table 1.

2.2 Agentic Maturity Rubric Evaluation

The technological maturity of the identified systems in emerging domains was evaluated using a six-dimensional agentic maturity rubric (D1-D6). The dimensions reflected the transition from traditional AI decision-support systems toward autonomous AI agents capable of operating across digital environments [1]. Using a six-dimensional agentic maturity rubric, each review finding was evaluated with LLM classification using a four-point scale (0–3), where 0 indicates the lowest or conceptual capability and 3 represents advanced implementations involving adaptive behavior, multi-agent coordination, or dynamic interaction with external digital environments.

The six-dimensional rubric used for study-level coding is presented in Table 2. For each finding, the dimensional scores were averaged to calculate the mean values. The mean values were then mapped to the ALoD maturity levels defined in Table 1 to position each finding in terms of technical agentic capability and its potential role in lifecycle-based circular construction workflows.

Table 1. Agentic LoD maturity levels and lifecycle interpretation

Maturity level	Label	ALoD	Interpretation
0	No agentic capability	Below ALoD	Review, conceptual mapping, and evidence of digitalization without an autonomous system.
1	Analytical decision-support systems	ALoD 100–200	Single model, DSS, basic tool-supported analysis; human is the primary decision-maker
2	Coordinated computational workflows	ALoD 300	Integrated BIM/DT/robotics workflow supporting structured automation, reuse assessment, and deconstruction planning.
3	Advanced agentic autonomy	ALoD 400–500	High integration with adaptive, robotic, DT-enabled, self-managed execution for autonomous management.

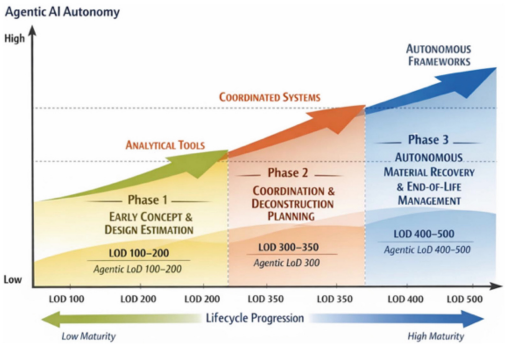


Fig. 1. BIM-AI maturity framework lifecycle diagram

Table 2. Six-dimensional agentic maturity rubric

Dimension	0	1	2	3
D1 Agency structure	No agent	Single analytical model	Coordinated workflow	Multi-agent, self-organizing agency
D2 Tool integration	No digital tool integration	Standalone model or software	BIM/DT, platform, robotics integration	Multi-tool, API, cloud integration
D3 Reasoning depth	Descriptive, review-level	Classification estimation	Rule-based planning, optimization	Iterative autonomous reasoning
D4 Adaptivity	Static, conceptual	Fixed data-driven model	Optimisation, scenario-responsive	Real-time feedback-driven adaptation
D5 Autonomy	No autonomous capability	Human in decision support	Automated workflow or execution	Autonomous, self-managed execution
D6 Environmental data resolution	Generic, conceptual	Document, survey, and generic data	BIM, material, building-level data	Sensor, reality-capture, robotic, DT, as-built data

3 Results and Discussion

3.1 Pairwise Domain Relationship Mapping Results

In the pairwise domain mapping analysis, the strongest relationship observed in the literature was between circular construction and AI-enabled BIM/DT infrastructures**.** Within this subset, studies demonstrated that digital material passports and lifecycle data platforms can support circular decision-making throughout the building lifecycle, particularly for reuse planning strategies [11, 19]. Contributions highlighted the integration of BIM with advanced digital technologies such as blockchain, IoT, and AI-supported analytics to improve transparency and traceability in supply chains [12, 14, 17]. Most contributions have remained focused on information structuring, assessment, and decision support rather than autonomous execution.

The second relationship concerned the integration of agentic AI systems within digital construction environments. Most studies fell into digital lifecycle infrastructure, focusing on broader construction automation problems. This confirms the central gap addressed by the proposed framework: while agentic AI research has advanced automation capabilities, the two trajectories have not yet been systematically integrated.

3.2 Agentic Maturity Assessment Results

The technological maturity of the identified systems was evaluated using the six-dimensional agentic maturity *rubric* presented in Table 2. The complete study-level coding matrix for all 37 analyzed publications is presented in Table 3. Accordingly, among the 37 analyzed publications, 11 studies were classified as having no agentic capability, corresponding to 29.7% of the corpus, while 10 studies were classified as analytical decision-support systems, representing 27.0%. The largest group consisted of 13 studies classified as coordinated computational workflows, corresponding to 35.1%. Only three studies, 8.1% of the corpus, reached the level of advanced agentic autonomy.

Table 3. Maturity level results of Agentic AI use through the analyzed publications

Ref.	D1	D2	D3	D4	D5	D6	Mean Score	Maturity Level	Agentic LoD (AloD) Category
[36]	1	1	2	1	1	1	1,17	1	ALoD 100–200
[37]	1	1	2	1	1	2	1,33	1	ALoD 100–200
[38]	1	1	1	1	0	3	1,17	1	ALoD 100–200
[39]	2	2	1	1	2	3	1,83	2	ALoD 300
[40]	1	1	1	1	1	2	1,17	1	ALoD 100–200
[41]	1	2	2	2	1	2	1,67	2	ALoD 300
[42]	2	3	2	2	2	3	2,33	3	ALoD 400–500
[43]	1	1	2	1	1	2	1,33	1	ALoD 100–200
[44]	1	2	1	1	2	2	1,50	2	ALoD 300
[45]	2	3	2	2	3	3	2,50	3	ALoD 400–500
[46]	2	2	1	1	2	2	1,67	2	ALoD 300
[47]	0	1	1	0	0	1	0,50	0	Below ALoD
[11]	0	1	1	0	0	1	0,50	0	Below ALoD
[12]	0	1	0	0	0	1	0,33	0	Below ALoD
[13]	0	1	1	0	0	1	0,50	0	Below ALoD
[14]	1	2	2	1	1	2	1,50	2	ALoD 300
[15]	0	1	1	0	0	1	0,50	0	Below ALoD
[16]	1	2	2	2	1	2	1,67	2	ALoD 300
[17]	1	2	1	1	1	2	1,33	1	ALoD 100–200
[18]	0	1	1	0	0	1	0,50	0	Below ALoD
[19]	1	1	1	1	0	1	0,83	1	ALoD 100–200
[20]	0	1	1	0	0	1	0,50	0	Below ALoD
[21]	1	2	2	2	1	2	1,67	2	ALoD 300
[22]	0	1	1	0	0	1	0,50	0	Below ALoD
[23]	0	1	1	0	0	1	0,50	0	Below ALoD
[24]	1	2	2	1	1	2	1,50	2	ALoD 300
[25]	1	2	1	1	1	2	1,33	1	ALoD 100–200
[26]	0	1	1	0	0	1	0,50	0	Below ALoD
[27]	1	2	1	1	1	2	1,33	1	ALoD 100–200
[28]	1	3	2	1	1	2	1,67	2	ALoD 300
[29]	2	3	2	1	2	2	2,00	2	ALoD 300
[30]	1	2	2	2	1	2	1,67	2	ALoD 300
[31]	1	2	1	1	1	2	1,33	1	ALoD 100–200
[32]	0	1	1	0	0	1	0,50	0	Below ALoD
[33]	1	2	2	1	1	2	1,50	2	ALoD 300
[34]	1	2	2	1	1	2	1,50	2	ALoD 300
[35]	2	3	2	2	2	3	2,33	3	ALoD 400–500

4 Conclusion

The fundamental technological components for circular construction are largely available in terms of BIM and DTs, providing structured data infrastructure, and agentic AI, providing task decomposition and autonomous decision-making logic. This study offers three key contributions. First, it systematically reveals the relationships among circular construction, BIM, DT infrastructure, and agentic AI through binary domain mapping. Second, it examines the current level of agentic AI development using a multidimensional evaluation rubric encompassing agent structure, tool integration, reasoning depth, adaptivity, autonomy, and environmental data resolution. Third, it demonstrates that

circular construction workflows require different levels of AI support across lifecycle phases, each corresponding to increasing levels of BIM data reliability and AI autonomy.

The pairwise domain results revealed that an integrated approach to supporting circular lifecycle processes remains limited due to a lack of conceptual alignment between AI autonomy and BIM data reliability. Most agentic AI implementations are currently applied to operational construction processes rather than lifecycle-oriented decision-making, and increasing levels of AI autonomy remain only indirectly connected to circular construction strategies. This highlights a structural gap between digitally enabled circular construction infrastructures and emerging agentic AI technologies.

This study is limited to a maturity assessment based on a review. Future research can extend the framework through expert review, stakeholder-driven criteria mapping, and application within operational circular construction workflows.

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Ground Penetrating Radar for Circularity: Identifying Reusable Building Components Through Non-destructive Testing

Ourania Patsia(✉) and Alexandre Novo

Screening Eagle Technologies, 29004 Málaga, Spain
ourania.patsia@screeningeagle.com

Abstract. Construction and demolition activities generate significant amounts of waste, contributing to environmental degradation and reduction of raw materials. A promising solution to these issues is the reuse of building components. Promoting the reuse of building components through advanced detection and characterization methods can help address these challenges and support circular economy practices in the construction sector. This work explores the use of Ground Penetrating Radar (GPR) as a detection tool for identifying hidden materials in existing concrete-based and timber-based buildings that could be re-used in new constructions or for repairing/renovating old ones. In addition to detecting hidden components, GPR can also be used for material characteriza-tion. The effectiveness of GPR was determined by scanning different case studies of buildings that will be demolished. Data processing and interpretation were performed to demonstrate the components and information that can be identified with GPR, enhanced by automated interpretation techniques and augmented reality (AR) visualization. As demonstrated in this study, structural components (e.g., rebars, studs), insulation layers and other internal components can be detected in addition to voids and qualitative information regarding moisture content and deterioration. These findings demonstrate the potential of GPR to enhance material recovery and reuse strategies in building deconstruc-tion. This research is conducted as part of the SUM4Re project which aims to promote circularity in construction by creating material banks using different scanning techniques and innovative data-driven approaches to identify reusable materials in end-of-life buildings.

Keywords: non-destructive testing · ground-penetrating radar (GPR) · circular construction · sustainability

1 Introduction

Construction and demolition waste is among the largest waste streams globally, creating serious environmental, social, and economic challenges. Valuable materials such as concrete and wood are often discarded rather than recycled, resulting to the continued extraction of raw resources. The production of new materials as well as the disposal of existing ones contribute substantially to greenhouse gas emissions and environmental degradation. These challenges can be tackled by instead identifying reusable resources within

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existing buildings, promoting material recovery and reuse, and also circular economy practices that reduce waste and support more sustainable constructions.

SUM4Re is an initiative co-funded by the European Commission under the Horizon Europe research and innovation programme. The SUM4Re project seeks to reduce waste and accelerate the transition to circular economy models within the construction sector. Its primary objective is to develop comprehensive methodologies for identifying and characterizing materials, including hidden components, in end-of-life buildings, enabling valuable materials or components to be recovered and reused in new construction projects or renovation works. Different scanning technologies are investigated for identifying different materials. The project will also develop artificial intelligence (AI)-supported algorithms to enhance the interpretation of data collected through advanced scanning technologies. Ultimately, digital material banks will be established to ensure the traceability and efficient management of recovered materials and components [1].

Ground penetrating radar (GPR) is one of the investigated scanning techniques for the purposes of the SUM4Re project. GPR has become one of the most versatile and widely used methods in non-destructive testing (NDT). Its capability to investigate subsurface features without causing damage makes it highly valuable across numerous industries. It is commonly used for the inspection of concrete structures, assessment of bridge integrity, detection of underground utilities, evaluation of road conditions, archaeological exploration, and geological investigations, among many other uses [2]. Specifically for concrete structures, it is commonly used for detecting structural components such as rebars and post-tensioning cables, conduits, and others, as well as give information regarding the concrete condition.

Fundamentally, GPR is used to characterize subsurface materials, distinguish between different layers, identify buried objects and detect other anomalies. Its expanding use is largely due to its key advantages: it is non-invasive, allows for fast data collection, and provides high spatial resolution. The operating principle of GPR involves transmitting electromagnetic (EM) waves into a target material, such as soil, or concrete, through a transmitting antenna. As these waves propagate through the medium, they are partially reflected at interfaces where materials exhibit contrasting dielectric properties. The receiving antenna captures these reflected signals, and their amplitude and travel time reveal information about the depth and characteristics of subsurface features [3].

Although applications in concrete and soil are more prevalent, research and commercial usage of GPR for wood and timber structures are steadily increasing. It has been utilized for monitoring the internal condition of tree trunks, evaluating wooden utility poles, and examining other timber structures. Typical uses in wood assessment include detecting internal cracks, knots, moisture variations, and evaluating the overall condition of the wood [4–6].

This paper demonstrates the effectivity of repurposing GPR technology for the aims of material recovery and shows what information can be extracted with GPR regarding hidden components but also material characterization. This is shown with two case studies with different materials and structure, which present two out of three pilot sites for the SUM4Re project; a reinforced concrete structure in Spain and a timber-based building in Norway.

2 Methodology

2.1 Pilot Sites

The first pilot site comprises of two buildings located in San Sebastián, in the Basque Country of Spain: the Anoeta railway station and the Jolastokieta building. Originally, the building in Jolastokieta was an industrial facility where elevators were manufactured but in recent years, the building is abandoned. The floors are constructed from concrete slabs topped with a mortar layer and embedded steel rebars. In contrast, the walls are composed of brick and concrete and do not contain internal reinforcement. At present, the building stands empty, and several exposed external steel beams are visible on site. A photograph of this site can be seen in Fig. 1a.



Fig. 1. a. Jolastokieta building, Spanish pilot and b. Residential timber building, Nordic pilot

The second pilot site is located in Longyearbyen, Svalbard, Norway which is widely recognized as the world's northernmost inhabited settlement. This site consists of a two-storey residential building primarily constructed from timber. The structure is supported by foundation piles embedded in the permafrost layer, which historically has provided ground stability. The external walls are composed of multiple layers, including exterior cladding, asphalt panels, insulation materials, and fibreboard. The floor system is predominantly wooden and incorporates insulation and heating elements, while tiled finishes are present in areas such as the bathroom. Figure 1b shows an image of the exterior of the building.

Extreme weather conditions and the impacts of climate change on the permafrost have led to ground instability, compromising the building's structural support. This instability is one of the key reasons why this building, along with others of a similar type, has been selected for demolition. Given the site's remote Arctic location, transporting construction materials is both logistically challenging and costly, making material circularity and reuse from buildings about to be demolished particularly important [7].

2.2 System Used

For conducting the GPR scans, the Proceq GP8800 high-frequency system was selected. This is a step-frequency continuous-wave (SFCW) system with a modulated frequency range of 400–6000 MHz and its high frequency allows for resolving relatively small features. It has a maximum penetration depth of 65 cm which was sufficient for the investigated structures which have small thickness.

The transmitting and receiving antennas are in the same case and measures a total size of 8.9 x 8.9 x 7.6 cm making it compact, easy to transport and use in the field but also ideal for tight spaces. It is designed to operate in direct contact with the surface of the structure being scanned with its primary application being concrete scanning. Figure 2 shows an image of the sensor.



Fig. 2. The Proceq GPR GP8800 sensor with some of its features annotated

2.3 Data Collection and Processing

The data acquisition performed was similar to both sites. Grid scans of 60 x 60 cm were performed at different parts of the buildings, both in walls and floors. In a grid scan, measurement lines were collected at both x and y directions with spacing $\Delta x = \Delta y =$ 5 cm between lines. For scanning each area with accurate positioning, a grid paper was used which has marked the 0,0 origin and the parallel lines at each direction with 5 cm spacing. For each A-scan, a time window of 16 ns was recorded with 655 samples. The scans were performed with the antenna being in direct contact with the structure surface.

It is common after data collection to perform certain processing of the GPR data that will result in easier and more accurate interpretations. For all collected datasets, the following filter sequence was applied:

- Time zero correction: This is a vertical shift of the data to a certain sample such as the 0 m to represent the ground surface which is necessary for correct depth estimation.
- Noise cancellation: Frequency filter used for removing certain types of noise (e.g. from Wi-Fi or cell phones) from the data.
- Background removal: Reduces noise that appears as horizontal stripes in the data but also the strong direct wave response that might mask other objects.
- Gain: Signals are getting weaker with increasing depth making certain responses not visible. This filter is used to amplify the signal amplitudes and make these responses visible.

3 Results

3.1 Case Study 1: Spanish Pilot

Before starting the interpretation, it is important to set the dielectric constant value. This is a material electrical property which is necessary for accurate depth estimations. In this case, this was calibrated using a process called hyperbola fitting [8] and by utilizing the hyperbolic responses from the rebars. Across all scans, the dielectric was between 9 and 12 which are characteristic of wet concrete (dry concrete is typically between 5–8).

As expected, the reinforcing mesh embedded within the concrete floor slab was clearly detected and mapped, along with other linear features that may correspond to additional reinforcement elements or embedded pipes. An example is shown in Fig. 3 where in Fig. 3a, the scanned area along with the grid paper can be seen and in Fig. 3b, the GPR slice at ~18 cm depth in which the rebar mesh can be seen. In certain areas, small irregularly shaped anomalies were also identified, which could potentially indicate the presence of voids. Overall, the concrete slab exhibited a high moisture content. This assessment is supported by the high dielectric values, as well as by visible surface conditions observed on site. Therefore, the concrete in this case study is considered deteriorated. Figure 3c shows the B-scan for line 23, where the hyperbolas from the rebars can be seen in the data along with the high dielectric values calculated which show the condition in the vicinity of each rebar.

3.2 Case Study 2: Nordic Pilot

Similarly, the dielectric value was calibrated for the scans in the Nordic pilot. However in this case since hyperbolas were not present in the data, this was performed by utilizing the backwall response from the wall/floor and their known thickness. This resulted in dielectric values between 2 and 3 across all scans which are bulk values for the wall/floor as a whole and not separate for each constituent material.

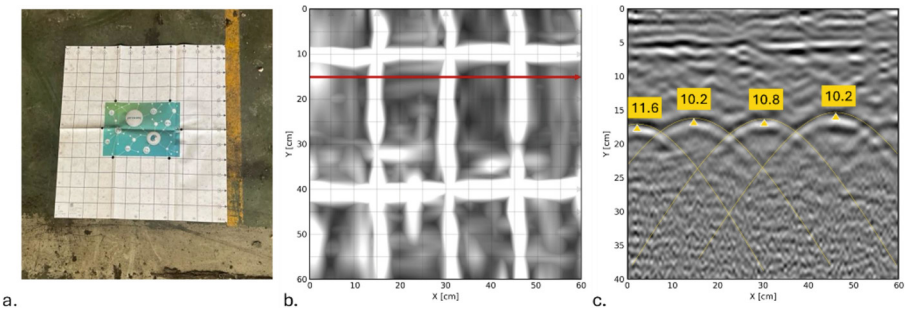


Fig. 3. a. Floor slab scanning location from Spanish pilot, b. Depth slice at ~18 cm depth showing the reinforcing mesh with rebars at both directions and line 23 highlighted and c. B-scan of line 23 showing the detected hyperbolic responses from rebars and the high dielectric values at the vicinity of each

From the GPR data over the floors, the heating elements, the vertical wooden beams (with hyperbolic responses) along with the insulation layer could be identified but also the interfaces between the insulation/cavity and insulation/fibre board (recorded as flat horizontal responses). The heating elements can be seen in the depth slice of Fig. 4a, where the data have are visualized on the scanning location utilizing the augmented reality (AR) feature directly on-site. Different responses from the heating elements and layers can be seen in the example B-scan data in Fig. 4b.

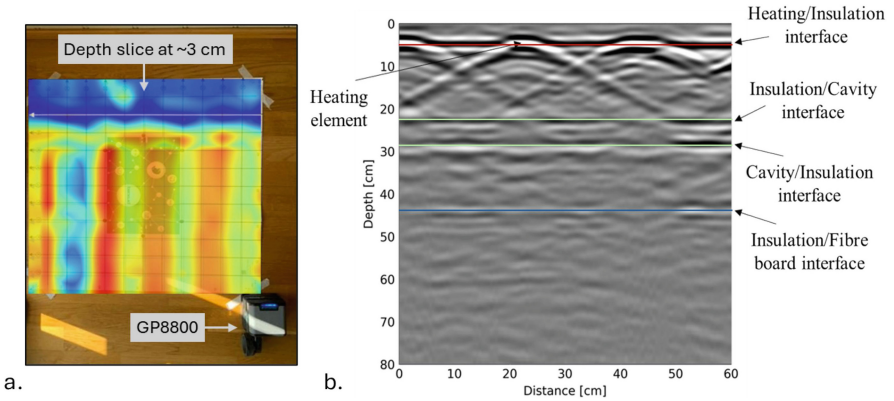


Fig. 4. a. Projected depth slice on the floor slab using the AR feature which shows the heating elements and b. Example B-scan from the floor data showing the different responses recorded

In the wall data, the vertical and horizontal wooden studs, insulation layers, and other similar layer interfaces could be identified. An example is provided in Fig. 5a where the vertical wooden stud is shown directly at the scanning location by projecting the data with the AR tool. In Fig. 5b, the hyperbola from the stud and the flat responses from the layer interfaces are also highlighted. Cabling or mesh within the wall was also identified as a sequence of hyperbolas in the same depth, as shown in Fig. 5c. Most walls seemed in a good condition with no anomalies detected, especially in the internal walls. However, certain external walls showed significant clutter which indicates the presence of higher moisture and/or voids in the wall structure such as the example displayed in Fig. 5d. Thus, based on the GPR data is speculated that this area is likely deteriorated.

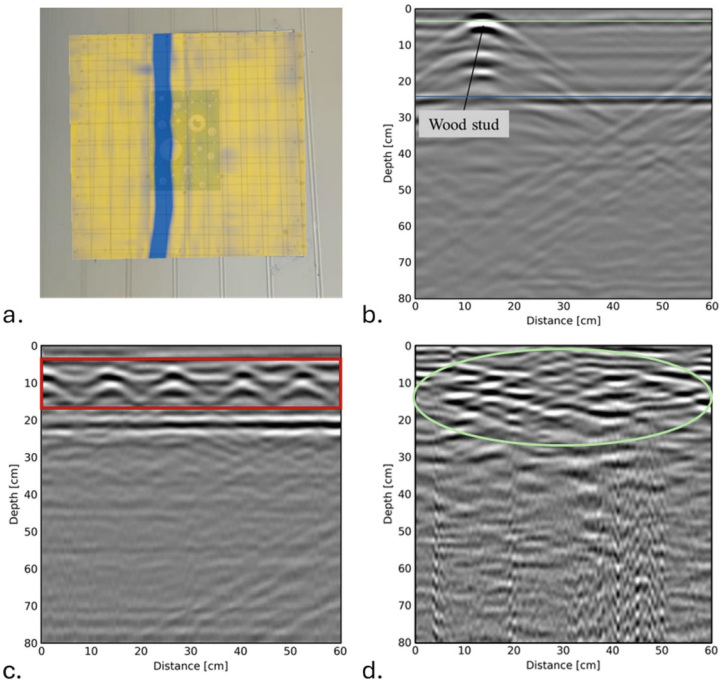


Fig. 5. a. Depth slice showing the vertical wooden stud inside the wall, b. B-scan example showing flat responses and hyperbola from wooden stud, c. Potential cabling or mesh in the wall response and d. Significant clutter in the data from external building walls

4 Conclusions

One of the primary GPR applications is the identification of embedded elements in concrete, such as reinforcing bars and post-tensioning cables, while also providing insight into the state of the surrounding concrete, including moisture content. For the Spanish pilot site, the objective of the GPR survey is to detect and characterize metallic reinforcement bars embedded within concrete slabs, while also assessing the condition of the concrete, including moisture levels and the potential presence of voids. This was achieved as shown by the results of the Spanish pilot with this information supporting selective cutting or deconstruction strategies, facilitating the recovery of steel reinforcement and the potential reuse of concrete elements.

The Nordic pilot results showed that for timber structures, GPR can be used to detect concealed components such as wooden studs and insulation layers, as well as to identify moisture accumulation but also internal voids. Additional reusable elements, such as metallic and non-metallic utilities, heating elements, and internal cabling typically embedded within walls and floors can also be located. More broadly, GPR is capable of scanning a wide range of construction materials, distinguishing between layers, and identifying embedded features, making it applicable beyond concrete and timber alone. Therefore, its applicability to different materials and structures along with different types of information that GPR can provide, ease of data collection and non-destructive

nature make GPR an efficient technique for selective deconstruction and useful reusable material identification.

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A Framework for Digital and Sustainable Classroom Management: Non-Intrusive CO_2-Based Occupancy Estimation for Demand-Controlled Ventilation

Graziano Salvalai(✉), Roberto Villa, and Manuela Grecchi

Politecnico di Milano, Milano 20133, Italy
graziano.salvalai@polimi.it

Abstract. Classrooms often present low Indoor Air Quality (IAQ) conditions, including in mechanically ventilated educational buildings where Constant Air Volume (CAV) HVAC systems operate on fixed schedules that do not account for real-time occupancy. This rigidity creates a critical trade-off: inadequate IAQ during peak usage and unnecessary energy consumption during low-occupancy periods. Addressing this issue requires accurate, real-time occupancy data, which is often unavailable due to cost or privacy constraints. This study analyses and validates a non-intrusive method for estimating real-time occupant counts using CO_2 concentration data. Measurements were collected in two adjacent classrooms with similar HVAC configurations during a long-term monitoring campaign in which indoor CO_2 levels were continuously recorded. A CO_2 mass-balance model was developed to incorporate sensor data and the constant air exchange rate of the HVAC system, enabling dynamic estimation of occupant-generated CO_2 and, consequently, occupant count. Model outputs were validated against scheduled occupancy data obtained from surveys. Results indicate that the method predicts occupancy patterns with an accuracy of approximately ±5%. With appropriate sensor placement, spatial occupancy distribution can also be inferred. Continuous monitoring revealed frequent CO_2 peaks above recommended thresholds during teaching hours, underscoring the limitations of static ventilation strategies in educational environments. The CO_2-based estimation model effectively captured these events, offering a cost-efficient and privacy-preserving proxy for real-time occupancy.

Keywords: Classroom · University · Thermal Comfort · Indoor Air Quality (IAQ) · Occupancy Estimation · CO_2 · Mass-Balance Model

1 Introduction and Related Works

The built environment plays a pivotal role in both climate change mitigation and human well-being. Buildings account for a substantial share of global final energy consumption and associated greenhouse gas emissions, largely due to heating, cooling, and ventilation demands. In educational buildings, where the number of occupants per unit area

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can be up to four times higher than in typical office spaces [1], Indoor Air Quality (IAQ) becomes a central concern [2, 3]. Carbon dioxide (CO_2) concentration is widely adopted as a proxy indicator for ventilation adequacy [4]. A CO_2 concentration of 1000 ppm is the de facto standard threshold for acceptable IAQ [5]; exceeding this limit, or reaching levels above 1500–2000 ppm, is linked to reduced cognitive performance and increased discomfort among students [6]. Maintaining adequate IAQ while limiting energy use is therefore a dual objective. In many existing university buildings, mechanical ventilation is provided by Air Handling Units (AHUs) in Constant Air Volume (CAV) mode, operated according to fixed schedules, independently of real occupancy. This creates structural inefficiencies since fixed airflow rates may be insufficient during peak occupancy, leading to a low level of IAQ, while supplying excess air during partial vacancy causes unnecessary energy consumption. Transitioning to adaptive control strategies, such as Demand-Controlled Ventilation (DCV), can yield substantial savings without compromising comfort [7, 8]. Implementing DCV requires reliable real-time occupancy data [9]. Existing occupancy estimation approaches generally fall into direct sensing, indirect environmental sensing, and data-driven methods. While direct sensing techniques (e.g., cameras, optical sensors) provide high accuracy, they suffer from high costs, and severe privacy concerns in educational contexts [10, 11]. Data-driven approaches require extensive labelled datasets and exhibit limited transferability [12]. Consequently, CO_2-based occupancy estimation offers a low-cost, non-intrusive alternative [13]. Since humans produce CO_2 proportionally to their metabolic activity, transient mass-balance formulations can be exploited to dynamically infer occupant counts [14]. This correlation heavily depends on the available volume per student and the ventilation rate [15]. Within a digital building management framework, this approach functions as a virtual sensor [16]. Despite its potential, CO_2-based estimation becomes highly complex under active mechanical ventilation, as the controlled introduction of outdoor air alters indoor CO_2 independently of human presence [10, 11]. If the exact amount of mechanical ventilation is not factored into the mass-balance equations, the model will systematically underestimate the occupant count. Furthermore, baseline outdoor CO_2 concentrations fluctuate daily [4, 17]; assuming a static outdoor baseline of 420 ppm introduces significant calculation errors. To address these gaps, this study proposes and validates a non-intrusive occupancy estimation framework based on transient CO_2 mass-balance modelling applied to mechanically ventilated university classrooms. The main objectives are: i) develop a model capable of estimating real-time occupant count, switching autonomously between mass-balance models based on the operational state of the AHU, ii) validate the model against scheduled occupancy data collected during a long-term monitoring campaign.

2 Methodology

The proposed methodology, schematized in Fig. 1, is based on a transient mass-balance equation describing indoor CO_2 concentration dynamics.

The model relies on three assumptions. These comprise i) reasonably well-mixed indoor air, ii) constant mechanical ventilation rates during operation, and iii) human respiration as the predominant CO_2 source. Standard metabolic rates define this human

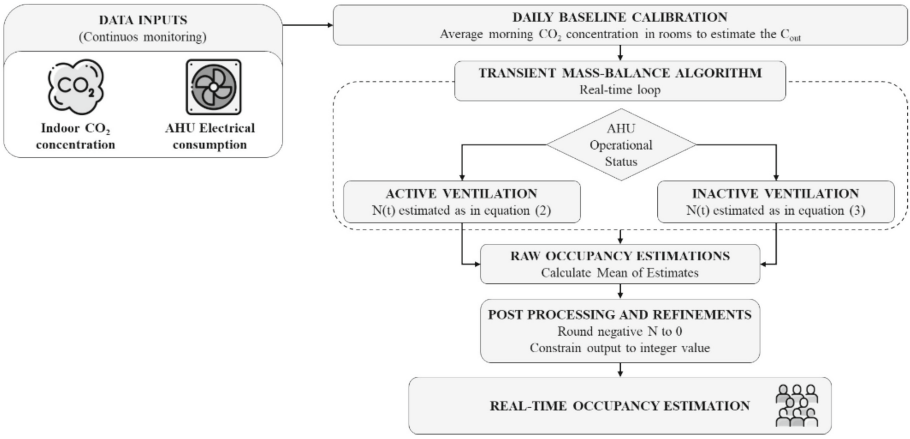


Fig. 1. Methodology framework for a non-intrusive CO_2-based occupancy estimation

generation. The general mass-balance differential equation (1) governs the temporal evolution of indoor CO_2 concentration [11].

$$\frac{dC(t)}{dt} = \frac{N(t) \bullet g}{V} - \frac{Q}{V} \bullet (C(t) - C_{out}) \tag{1}$$

where N(t) represents the number of occupants at time t. The parameter g defines the per-capita CO_2 generation rate, which in this study is set to 0.0052 L/s/person [15]. V denotes the room volume. Q indicates the ventilation airflow rate. C(t) and C_{out} represent the indoor and outdoor CO_2 concentrations, respectively. Discrete-time implementations apply Δt as the sensor sampling interval. $C_{initial}$ and C_{final} signify the indoor CO_2 concentrations at the beginning and end of each time step. The algorithm dynamically recalibrates C_{out} daily to ensure accurate estimations. This baseline derives from averaging the indoor CO_2 concentration measured during the pre-occupancy flushing period. This period spans from the morning activation of the air handling unit until 08.30. The system applies a default outdoor value if it detects no activation within this window. The algorithm adapts the occupant count calculation to the operational state of the mechanical ventilation. The electrical current drawn by the air handling unit continuously indicates this operational state. The system discretises the time series according to Δt. Equation (2) integrates the mechanical extraction of CO_2 over Δt during active ventilation periods.

$$N = \frac{Q}{g \bullet \left(1 - e^{-\frac{Q}{V}\Delta t}\right)} \bullet \left(C_{final} - C_{out} - (C_{initial} - C_{out}) \bullet e^{-\frac{Q}{V}\Delta t}\right) \tag{2}$$

Inactive ventilation periods assume Q equals zero. Equation (3) attributes all CO_2 variation exclusively to occupant generation under these inactive conditions.

$$N = \frac{\left(C_{final} - C_{initial}\right) \bullet V}{g \bullet \Delta t} \tag{3}$$

The algorithm rounds any negative values for N to zero to account for sensor noise. The final output is constrained to integer values. Large spatial volumes can introduce potential inaccuracies. The methodology limits these errors by averaging independent estimates. These estimates originate from the sensors positioned in the front and rear zones.

3 Case Study and Monitoring Setup

The experimental approach was validated during the DIGITMAN project [18–20], using two representative classrooms at the Politecnico di Milano, Lecco Campus. Designated as Classroom A and Classroom B. Both rooms feature a clear height of 3.8 m. Classroom A accommodates 200 seats within 373.02 m^2 and 1,417.48 m^3. It includes a north-facing curtain wall and a west-facing ribbon window. Classroom B provides 100 seats across 170.71 m^2 and 648.70 m^3. This room features a fully glazed western facade with two electrically operated casement windows. Dedicated CAV systems serve both rooms to maintain regulatory air exchange and thermo-hygrometric control. Classroom A receives 11,000 m^3/h of supply air. Classroom B receives 7,200 m^3/h.

The monitored classrooms are accessible on weekdays from 07:00 to 19:00 for fixed lectures and unstructured study. Mechanical ventilation operated daily from 07:00 to 18:00. A distributed sensor network monitored indoor conditions starting in March 2024. Two sensors per room measured carbon dioxide concentrations and other indoor parameters. These devices were suspended 3.0 m high in the front and rear zones (Fig. 2). Measurements were transmitted to a cloud platform at one-minute intervals. The system concurrently logged electrical current, energy consumption, and external weather conditions. Table 1 details the physical characteristics of the classroom and the technical specifications of the sensors employed in the study.

Table 1. Summary of experimental setup and sensor technical specifications

Category	Parameter	Unit	Value/Specification
Classroom A	Volume (V)	m^3	1,417.48
	AHU airflow (Q)	m^3/h	11,000
Classroom B	Volume (V)	m^3	648.70
	AHU airflow (Q)	m^3/h	7,200
Sensors	Air Temperature	°C	Operational range: - 40 to 80 °C Accuracy: ± 0.1 °C
	Relative Humidity	%	Operational range: 0 to 100% Accuracy: ± 1.5%
	CO_2 concentration	ppm	Operational range: 0 to 5000 ppm Accuracy: < (± 50 ppm +3%)

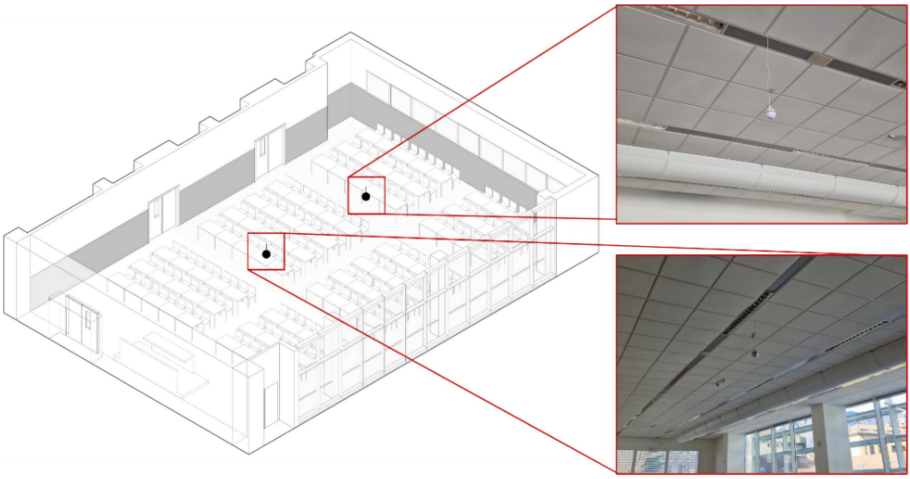


Fig. 2. CO_2 Sensor positioning in Classroom A; similar layout is used in Classroom B

4 Results and Discussion

Continuous monitoring demonstrated the inadequacy of static schedules for predicting ventilation requirements (Fig. 3). Unscheduled occupancy occurred frequently. Attendance during scheduled lectures rarely reached nominal capacity. This discrepancy caused significant over-ventilation. A CO_2-based mass-balance model captured these dynamic occupancy fluctuations accurately. Model predictions were compared against manual survey data. These observations were recorded at approximately hourly intervals during representative operational days. Occasional higher-frequency checks supplemented these routine measurements. The performance was assessed using the Mean Absolute Error (MAE).

Under steady-state conditions, the model achieved an average predictive accuracy of approximately ±5% with a MAE of ±3 occupants. This performance established the model as a reliable proxy. Current CAV systems operate inefficiently compared to established IAQ standards (Fig. 4) [5]. Classroom B supplies 7,200 m^3/h instead of the required 4,000 m^3/h. This causes a structural over-ventilation of 44%. Classroom A supplies 11,000 m^3/h, which exceeds its 8,000 m^3/h normative threshold.

Implementing demand-controlled ventilation with this virtual sensor provides substantial energy conservation. The power consumption of air handling unit fans is proportional to the cube of the airflow rate (Eq. 4).

$$P_2 = P_1 \bullet \left(\frac{Q_2}{Q_1}\right)^3 \tag{4}$$

Adjusting airflow to actual occupancy significantly decreases fan power consumption. Operating in Variable Air Volume mode reduces air velocities across the integrated heat exchanger. This reduction increases contact time and enhances both thermal and latent heat recovery. Several parameters influence the accuracy of the estimation model.

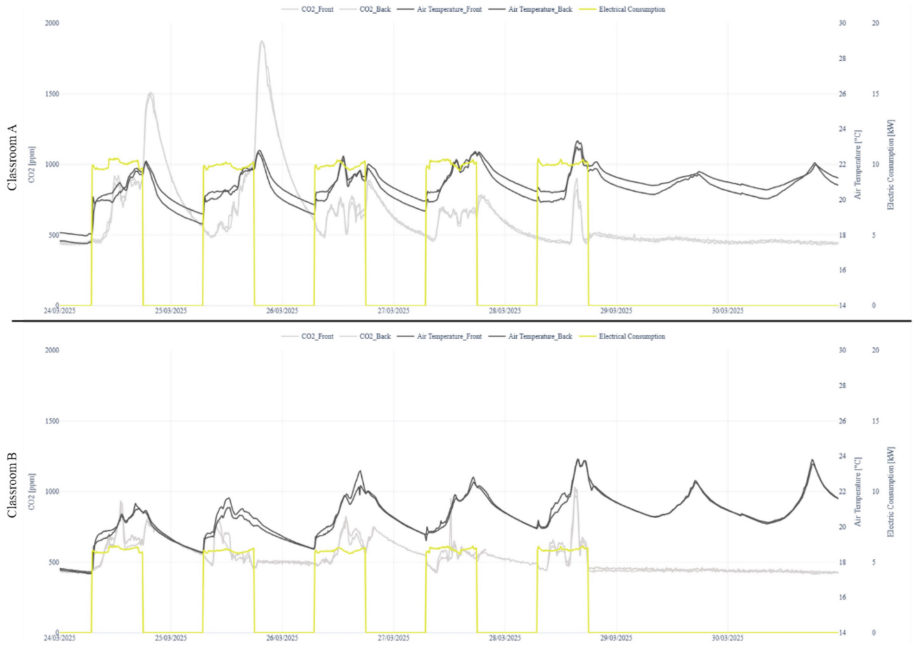


Fig. 3. Monitoring results during a representative week. Up: results for Classroom A; down: results for Classroom B

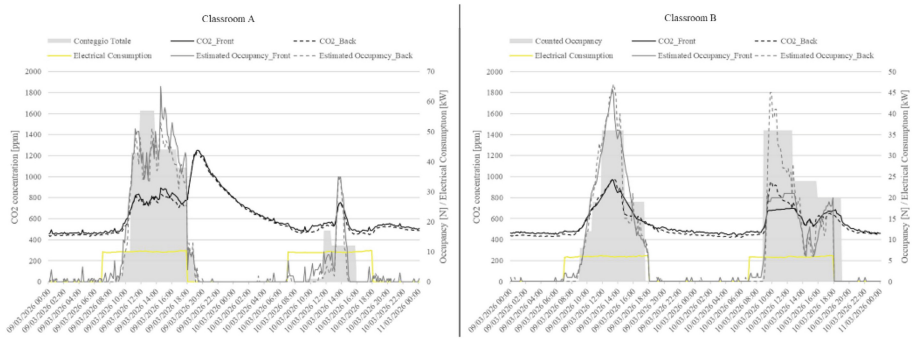


Fig. 4. Comparison of predicted occupancy (grey lines) compared with measured occupancy (light grey area) across two days. Left: results for Classroom A; right: results for Classroom B

These factors include i) the per-capita carbon dioxide generation rate, ii) the assumption of well-mixed air, and iii) the dynamic recalibration of the outdoor baseline. Variations in metabolic activity can introduce deviations in the generation rate. Dual-zone sensors effectively mitigate errors from local concentration gradients. Dynamic outdoor baseline recalibration prevents systematic errors associated with assumed static concentrations.

5 Conclusion

This study validated a non-intrusive, privacy-preserving framework for real-time occupancy estimation. The method employs CO_2 sensors in mechanically ventilated university spaces. The proposed model achieves an accuracy of $\pm 5\%$ without the costs or privacy risks of optical sensors. Results indicate current CAV operations cause a structural energy waste of at least 44%. Over-ventilation during periods of low occupancy causes this inefficiency. An occupancy-based demand-controlled ventilation strategy ensures healthy indoor air quality. This approach complies with regulations while reducing the building carbon footprint through lower fan power. The mass-balance model assumes constant mechanical ventilation. This assumption excludes transient natural ventilation events like window or door openings. System accuracy depends on precise spatial sensor placement. Appropriate positioning remains necessary to capture representative average concentrations in large volumes. Future work will i) integrate virtual sensors into Building Management Systems, ii) quantify thermal savings from optimised heat recovery, and iii) apply machine learning to adapt metabolic emission rates.

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Modeling the Effect of Carbon Nanotube Impregnation Conditions on Wood Properties Using Artificial Neural Networks

Sibel Yildiz[1](✉), Ayşenur Gürgen[2], and Ümit Cafer Yildiz[1]

[1] Faculty of Forestry, Karadeniz Technical University, Trabzon, Türkiye
sibelyildiz@ktu.edu.tr

[2] Faculty of Engineering and Natural Sciences, Osmaniye Korkut Ata University, Osmaniye, Türkiye

Abstract. Impregnation is a process within the discipline of wood preservation. Its purpose is to protect wood against all kinds of biotic and abiotic pests in various applications in the most economical way, using appropriate impregnation agents and methods to ensure optimal and long-lasting durability. This study aimed to impregnate Scots pine wood samples used in the impregnation industry with carbon nanotubes prepared at different concentrations (2% and 3%) using the full-cell method and to standardize these processes. For this purpose, the impregnation process was carried out with the specified tree species woods using impregnants of different concentrations by varying the pre-vacuum time and value (5 and 10 min and 60 cmHg vacuum), pressure time and values (10 and 20 min and 4, 6, and 8 atm pressure), and keeping the final vacuum time and value (5 min and 60 cmHg vacuum) constant. The retention (adhesion, kg/m^3) values, water uptake rates, and compression strength parallel to the grain of the impregnated wood samples were determined. These data were modeled with artificial neural networks. In this context, the impregnation material concentration, pre-vacuum time, pressure value and time were used as input information; and the retention amounts, water uptake rate, and compression strength parallel to grain were entered as outputs. The mean absolute percentage error (MAPE) for all models obtained was below 1%. As a result, models that can predict the intermediate values of the study with very high accuracy were obtained. It was concluded that ANN applications can be used with extremely high reliability and accuracy in such applications within the wood preservation discipline.

Keywords: Impregnation · Wood · Carbon Nanotubes · Modeling · Nano-Sized Materials · Retention

1 Introduction

Numerous studies have reported the application of artificial neural networks (ANNs) in the wood and timber industry for modeling production processes and predicting material properties. In this context, ANN models have been successfully applied to estimate drying rates in kiln-drying processes of lumber, demonstrating higher prediction accuracy

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compared to traditional modeling [1]. Similarly, ANN-based data fusion methods have been utilized in moisture content sensing systems for timber, improving the reliability and precision of moisture measurements [2]. In studies focusing on wood material classification, artificial neural networks have been combined with image-based analysis techniques for veneer classification, and the integration of evolutionary feature selection methods has been shown to significantly enhance classification performance [3].

ANN models have also provided important contributions to process optimization and quality control in manufacturing environments. For instance, artificial neural networks have been employed to predict and control surface roughness in CNC turning operations, successfully modeling the complex relationships between machining parameters and surface quality [4]. In addition, ANN applications in variable process control have demonstrated considerable advantages in monitoring and managing production performance in particleboard manufacturing (Esteban, Fernández, De Palacios, & Conde, 2009). In research investigating the mechanical properties of structural plywood panels, ANN models have been used to predict parameters such as modulus of rupture (MOR) and modulus of elasticity (MOE), and these models were found to provide higher predictive accuracy compared to multivariate regression approaches [5].

Furthermore, hybrid approaches combining neural networks with decision tree methods have been developed for the classification of wood veneer images, yielding promising results for material quality assessment [6]. In studies examining the mechanical performance of heat-treated wood, ANN models have also been applied to predict compressive strength, and these models have been shown to outperform multiple linear regression models in terms of predictive capability and reliability [7]. Collectively, these studies highlight the effectiveness of artificial neural networks as powerful tools for modeling production processes, predicting material properties, and supporting quality control applications in wood science and wood-based industries. The aim of this study was to investigate the effects of carbon nanotube–based impregnation parameters on the retention, water absorption behavior, and compressive strength parallel to the grain of *Pinus sylvestris* wood, and to develop artificial neural network models capable of accurately predicting these properties based on the applied treatment conditions.

2 Material and Method

2.1 Wood Species

Scots pine (*Pinus sylvestris*) wood samples, commonly used in the impregnation industry, were evaluated in this study.

2.2 Impregnation Agents

As the impregnation agent, nano-sized carbon nanotubes prepared at different concentrations (2% and 3%) using distilled water as the solvent were utilized.

2.3 Impregnation Conditions

The full-cell process was applied as the impregnation method. Scots pine wood samples were impregnated using solutions with different concentrations by varying the pre-vacuum duration and level (5 and 10 min at 60 cmHg vacuum), pressure duration and levels (10 and 20 min at 4, 6, and 8 atm pressure), and final vacuum duration and level (5 min at 60 cmHg vacuum). Following the treatment, retention values were determined.

2.4 Retention Amount

The retention amount of the experimental samples (R, kg/m^3) was calculated using Eq. (1) given below.

$$R\left(kg/m^3\right) = (G \times C)/V \times 10 \tag{1}$$

In this formula: R = Retention amount (kg/m^3); G = $T_2 - T_1$, where G represents the amount of impregnating agent absorbed (g); T_1 = weight of the sample before impregnation (g); T_2 = weight of the sample after impregnation (g); C = solution concentration (%); V = sample volume (cm^3).

2.5 Water Absorption Ratio (WAR)

Samples measuring of 3 × 3 × 1.5 cm were used to calculate the water absorption ratio (WAR). The impregnated samples were dried in an oven at 103 ± 2 °C until they reached a constant weight, and their oven-dry weights and dimensions were determined. Subsequently, the samples were placed in a certain amount of water with a weight applied on top to keep them fully submerged. During the immersion period of 336 h (2 weeks—the final measurement time according to the standard), the amount of water absorbed and the dimensional changes of both experimental and control samples were measured. For this purpose, at the end of each measurement period, the samples were removed from the water, the excess surface water was wiped off, and measurements were taken with the same precision. Using the initial oven-dry weight values, the water absorption ratio (WAR, %) was calculated separately for each experimental and control sample. WAR was calculated according to Eq. (2).

$$WAR(\%) = \left(\frac{M_2 - M_0}{M_0}\right) \times 100 \tag{2}$$

M_0: Initial oven-dry weight (g); M_2: Weight of the sample removed from water after each measurement period (g).

2.6 Compressive Strength Parallel to Grain

The compressive strength tests were conducted in the laboratories of the Department of Forest Industrial Engineering, Faculty of Forestry, Karadeniz Technical University, using universal testing machines in accordance with the TS-2595 (1977) standard. The

test samples were prepared with dimensions of 20 × 20 × 30 mm and conditioned at 20 °C and 65% relative humidity. After conditioning, the samples were air-dried, and their width and thickness were measured before testing. These measurements were performed from the middle section of each specimen using a micrometer with a precision of ±1 mm. During the test, a uniform loading rate was applied to the specimens' cross-sections so that they could be crushed within 2 min. The load was continuously applied until the specimen failed, and the maximum load value at the moment of failure was recorded from the machine dial. By measuring the force at failure (F_{max}), the compressive strength parallel to the grain ($\sigma_{B//}$) was calculated using Eq. (3) given below.

$$\sigma_{B//} = \frac{F_{\max}}{a \times b}\left(\frac{N}{mm^2}\right) \tag{3}$$

Fmax: Force at the moment of failure (N); a: Side length of the cross-section of the sample (mm); b: Side length of the cross-section of the sample (mm)

2.7 Modeling with Artificial Neural Networks

The modeling process was carried out by creating an ".m file" code in the MATLAB software environment. In the models, which had a feedforward network architecture and consisted of a single hidden layer, the backpropagation learning algorithm was used as the training algorithm. In addition, the Levenberg–Marquardt (LM) and Scaled Conjugate Gradient (SCG) algorithms were selected as optimization algorithms. For each model, two different optimization algorithms and fifteen different hidden neuron numbers (5–20) were compared in order to determine the most suitable network architecture. The learning rate and momentum coefficient were both set to 0.5, the maximum number of iterations was 1500, the validation check number was 500, and the target error value was determined as 1×10^{-5}. The performance of the obtained models was evaluated using the mean squared error (MSE), mean absolute percentage error (MAPE), and the coefficient of determination (R^2) Eqs. 4–6, respectively

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(e_i - p_i)^2 \tag{4}$$

$$MAPE(\%) = \frac{1}{n}\sum\left|\frac{e_i - p_i}{e_i}\right| \times 100 \tag{5}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(e_i - p_i)^2}{\sum_{i=1}^{n}(e_i - \overline{e})^2} \tag{6}$$

In the equations, n represents the number of data points, e_i represents the actual value, $\overline{e}$ represents the mean of the actual values, and p_i represents the predicted value generated by the model.

3 Results and Discussion

The ANN model data table for the samples impregnated with carbon nanotubes is presented in Table 1.

Table 1. The test results for the samples impregnated with carbon nanotubes

Pre-vacuum time (min)	Pressure time (min)	Pressure level (atm)	Impregnation concentration (%)	Retention (kg/m^3)	Water absorption ratio (%)	Compressive strength parallel to grain (N/mm^2)
5	10	4	2	13.07	90.45	552.46
5	10	6	2	13.25	90	556.31
5	10	8	2	13.4	90.56	550.03
5	20	4	2	13.5	89.95	550.45
5	20	6	2	13.56	89.9	551.3
5	20	8	2	13.65	89.88	549.67
10	10	4	2	13.69	87.56	556.08
10	10	6	2	13.87	87.5	559.93
10	10	8	2	14.02	87.41	553.65
10	20	4	2	14.12	87.3	554.07
10	20	6	2	14.18	86.83	554.92
10	20	8	2	14.27	86.5	553.29
5	10	4	3	19.09	88.22	559.23
5	10	6	3	19.27	87.77	563.08
5	10	8	3	19.42	87.33	556.8
5	20	4	3	19.52	87.72	557.22
5	20	6	3	19.58	87.67	558.07
5	20	8	3	19.67	87.65	556.44
10	10	4	3	19.18	85.33	562.85
10	10	6	3	19.36	85.27	566.7
10	10	8	3	19.51	85.18	560.42
10	20	4	3	19.61	85.07	560.84
10	20	6	3	19.67	84.6	561.69
10	20	8	3	19.76	84.27	560.06

Overall, higher impregnation concentration, longer pre-vacuum duration, and higher pressure levels tend to increase the retention amount while reducing the water absorption ratio. In terms of mechanical properties, although no substantial changes were observed in the compressive strength parallel to the grain, slight improvements were detected under certain treatment combinations. These findings indicate that carbon nanotube impregnation plays a particularly significant role in influencing retention and water

absorption behavior, while its effect on mechanical properties appears to be more limited but generally positive.

Performance of the Best Selected ANN Model for Carbon Nanotube–Impregnated was presented in Table 2.

Table 2. Performance of the Best Selected ANN Model for Carbon Nanotube–Impregnated

Tested Parameter	Performance	Training	Validation	Test	Overall
Retention	MSE	0.000935	0.02313	0.005586	0.004369
	MAPE	0.170894	112.859	0.484938	0.276872
	R	0.999944	1	1	0.99977
Water Absorption Ratio	MSE	0.000343	0.3121	0.202339	0.064591
	MAPE	0.017053	0.641358	0.531378	0.111939
	R	0.99995	1	1	0.990726
Compressive Strength Parallel to Grain	MSE	0.006131	0.292559	0.046989	0.047553
	MAPE	0.010664	0.119484	0.047894	0.022834
	R	0.999827	1	1	0.998881

The performance results indicate that the artificial neural network model achieved very high prediction accuracy for all investigated properties. The coefficient of determination (R) values are extremely close to 1, both in the training phase and in the validation and test datasets, demonstrating a strong agreement between predicted and experimental values. In particular, the overall R values of 0.999 for retention, 0.990 for water absorption ratio, and 0.998 for compressive strength parallel to grain confirm that the model has a very high predictive capability. Similarly, the MSE values obtained for the three parameters are quite low, indicating minimal deviation between predicted and observed values. Among the tested properties, the retention model shows the lowest overall error values, suggesting that the ANN model is particularly effective in predicting retention behavior. Although slightly higher error values were observed in the validation phase for water absorption ratio and compressive strength, the overall performance metrics still demonstrate a strong predictive performance. The MAPE values further support the accuracy of the models, as the overall percentage errors remain at very low levels. These results collectively suggest that the developed ANN model can reliably estimate retention, water absorption ratio, and compressive strength parallel to grain in carbon nanotube–impregnated wood samples, making it a powerful predictive tool for evaluating impregnation performance and related wood properties.

Although the ANN models showed high predictive accuracy, the present study was based on a limited and relatively homogeneous dataset. Therefore, model generalizability to different wood species, broader impregnation conditions, and varying environmental conditions should be interpreted cautiously. Future studies should test the model with larger datasets and compare its performance with alternative modeling approaches.

4 Conclusion

In conclusion, the results of this study demonstrate that impregnation parameters and carbon nanotube concentration significantly influence the retention capacity, water absorption behavior, and to a lesser extent the mechanical performance of *Pinus sylvestris* wood. Increasing impregnation concentration, pressure level, and treatment duration generally enhanced retention values, indicating more effective penetration of the impregnating agent into the wood structure. At the same time, higher retention levels were associated with reduced water absorption, suggesting that carbon nanotube impregnation contributes to improved dimensional stability by partially limiting water uptake. Although the compressive strength parallel to the grain did not exhibit large variations among treatment conditions, slight improvements were observed in several parameter combinations, indicating that the treatment does not adversely affect the mechanical integrity of the wood. Furthermore, the artificial neural network models developed in this study showed very high predictive performance, with extremely high determination coefficients and low error values, confirming that ANN-based approaches can successfully estimate retention, water absorption, and compressive strength based on processing parameters. Overall, the findings highlight the potential of combining carbon nanotube impregnation and ANN-based modeling as an effective strategy for predicting and optimizing the performance of impregnated wood materials.

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AI-Assisted Reading of Sensory Heritage: An MCP-Oriented Approach to the Multimodal Analysis of Emotional Change in Historical Urban Nodes

Serap Durmuş Öztürk[1](✉), M. Enes Öksüz[2], and Ercüment Öztürk[1]

[1] Karadeniz Technical University, Trabzon, Turkey
{serapdurmus,ercumentozturk}@ktu.edu.tr
[2] Avrasya University, Trabzon, Turkey
muhammet.oksuz@avrasya.edu.tr

Abstract. Historical urban nodes are complex heritage environments shaped not only by physical traces but also by sensory and emotional layers emerging from embodied user experiences. Within the scope of a TÜBİTAK-supported international project, this study reinterprets the sensory heritage of the Bedesten in Trabzon, Turkey, by analyzing concepts and sketches produced by participants through seeing, hearing, smelling, tasting, and touching using an AI-assisted model. Integrating Pallasmaa's multisensory architecture with Merleau-Ponty's philosophy of embodied perception, the study emphasizes sensory–emotional sustainability. Sketches (visual impression and conceptual) and textual emotion expressions were combined to construct a multimodal emotional resonance map. Processed through an unsupervised Self-Organizing Map (SOM), these data generate a spatial emotional topology. The proposed Model–Concept Protocol (MCP) organizes multimodal sensory data and offers a framework for digitally interpreting the emotional identity of historical urban environments, supporting sensory heritage documentation and the long-term sustainability of heritage assets

Keywords: Sensory Heritage · Emotional Sustainability · Multimodal Analysis · Artificial Intelligence and SOM · MCP (Model-Concept Protocol)

1 Introduction

Urban space is a complex phenomenon shaped by sensory and emotional interactions, which are essential to understand cities as unique fields of knowledge (Durmuş Öztürk & Çıraklı, 2023). Senses and emotions are very influential in the way people perceive urban spaces and therefore are very important in the formation of the spatial experience. Historical urban nodes are characterized not only by their physical features but also by the sensory and emotional experiences generated through embodied interactions.

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In architectural discourse, the multisensory character of spatial experience is increasingly acknowledged as a crucial factor in the perception and memory of environments (Pallasmaa, 2005; Böhme, 2017). However, heritage studies often focus on material conservation and the visual, ignoring the sensory and affective layers that contribute to the experienced dimension of historic places. Recent advances in digital technologies and artificial intelligence open up new possibilities for the integration of experiential data in architectural analysis. The paper proposes an MCP-oriented modeling approach for studying emotional transformations in sensory heritage environments. The Bedesten in Trabzon, Turkey in a TÜBİTAK supported urban route: The model-concept protocol (MCP) and self-organizing map (SOM) modeling for the analysis of sensory heritage and emotional dynamics of historical urban nodes.

2 Conceptual Framework of Sensory Heritage Modeling

Urban historic continuity is maintained not only through physical structures, but also through multi-sensory interactions and emotional responses that are elicited in spatial contexts by users. The importance of sensory perception and spatial atmosphere for the creation of human experience has been long recognized in architectural theory (Pallasmaa, 2005), but heritage documentation practices have mostly been confined to visual and material attributes. Consequently, it is challenging to systematically document and interpret the complex sensory and affective layers that constitute the lived experience of historic environments. Recent studies have pointed to the limitations of object-centred heritage archives and their visual bias in representing embodied and multisensory experiences (Hou et al., 2022). Such a limitation emphasizes the need for computational methods and defined protocols to interpret multimodal sensory data.

2.1 Sensory Heritage and Multimodal Spatial Emotion Modeling

Sensory architecture is a primary medium in the intergenerational transmission of collective memory, but it is troubled in urban settings with histories of rupture. This has prompted interest in sensory–emotional sustainability, focusing on the documentation of the experiential dimensions of urban heritage. The merging of experience and technology is essential to the creation of knowledge as cities evolve. Heritage contributes to local identity and sustainability. As suggested by research, the emotional resonance in digital heritage environments relies on well-structured multimodal configurations (Zhang & Du, 2025). New research opportunities arise with advances in technology and data-driven analysis methods (Picon, 2010; Carpo, 2017). Spatial emotion modeling studies user-space relations and discovers patterns from computational data. Affective computing, and more broadly, artificial intelligence tools, offer a better way to explore emotional experiences (Picard, 2000). Multimodal machine learning enables the combination of different data types (Baltrušaitis et al., 2017). The study uses sketches and textual emotion expressions in a multimodal data set analyzed by Self Organizing Map (SOM) to produce a spatial emotional topology that emphasizes the axes of emotional transformation.

2.2 Why a Protocol? The Need for MCP

Historical spaces are intricate systems influenced by sensory perceptions and embodied experiences. Conventional cultural heritage research has primarily emphasized visual and material elements, neglecting sensory and emotional aspects. This study introduces the Model–Concept Protocol (MCP) as a framework for organizing and interpreting sensory data in urban settings. By incorporating sketches and textual emotional expressions, MCP facilitates AI-supported analysis of the physical and experiential characteristics of historical spaces.

3 Methodological Framework

3.1 Research Context: Bedesten as a Historical Urban Node

Trabzon's Bedesten is an important commercial and social center, serving as a covered bazaar for precious goods and a gathering place for diverse social groups. Its architectural significance comes from its function in the historical trade network of Trabzon (Tuluk & Üstün, 2007). It is strategically located in the bazaar district and linked to caravanserais and markets, and it is an example of Ottoman urbanism that encourages economic activity and social interaction (Cerasi, 1999). Originally a part of key trade routes, it has moved from a busy commercial centre to a place of cultural heritage and tourism, showing changes in the collective memory of the city (Lowry, 2010). This paper explores the Bedesten as a historical urban node where the interactions of its users produce sensory and emotional experiences.

3.2 Data Structure and Preprocessing

The study examines the user experiences at Trabzon Bedesten by employing a dataset of multi-layered sensory data obtained from textual emotional expressions and sketches of 24 architecture students. The analysis was performed with text preprocessing by applying natural language processing (NLP) techniques, including text cleaning and TF-IDF transformation for numerical feature representation. Each student took part in a 45–60 min sensory exploration session and produced 48 sketches and documented associated sensory and emotional experiences. The project was funded by TÜBİTAK (223 K212) and voluntary participation and anonymization of data during processing were guaranteed.

$$TFIDF(t,d) = TF(t,d) \times \log\left(\frac{N}{DF(t)}\right) \tag{1}$$

The visual data sketches were digitized and image processing techniques were used to extract features. The included image features were edge density, shape distribution, and line orientation parameters. All the data obtained after the preprocessing were converted into digital feature vectors and a suitable data structure was generated for analysis.

3.3 Multimodal Modeling Architecture

The research uses a multimodal data modeling approach to analyze different types of data within a unified framework. This improves the analysis by integrating different sensory layers of spatial experience. It utilizes an artificial intelligence technology with a two-dimensional array structure.

$$X = \left[X_{text}, X_{image}\right] \tag{2}$$

3.4 Sensory Vector Space

For the analysis of multidimensional array data a common representation of all data types is important and it is given by the sensory vector space approach. The framework offers a common context for diverse data types about spatial experiences. As shown in Eq. (3), the differences of two samples of sensory data are intended to estimate the similarities of different user experiences.

$$d(x, y) = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2} \tag{3}$$

The study used textual and visual data from participants to produce sensory vectors. It classified textual data into five sensory categories—sight, hearing, smell, touch and taste—and linked emotional concepts to them. Visual sketches were divided and categorized according to the main sensory references. Frequency counts revealed the presence of all sensory and emotional categories in the responses of participants, which were subsequently normalized and transformed into numerical vectors for multimodal processing in a shared feature space.

3.5 Self-Organizing Map Implementation

We applied a classifying method of sensory data pattern based on the Self-Organizing Map (SOM) of unsupervised learning. The SOM model is an artificial neural network that maps high-dimensional data onto a two-dimensional map, with each neuron represented by a weight vector.

$$w_j = \left[w_{j1}, w_{j2}, \ldots, w_{jn}\right] \tag{4}$$

The nearest neuron (Best Matching Unit – BMU) was determined for each data sample, and weights were calculated as shown in Eq. (6) and used to position similar data samples close to each other on the map. x, w_j, $\alpha(t)$ and $h_{cj}(t)$ represent input vector, neuron weight vector, learning coefficient, neighborhood function respectively.

$$BMU = argmin_j \parallel x - w_j \parallel \tag{5}$$

$$w_j(t+1) = w_j(t) + \alpha(t) \cdot h_{cj}(t) \cdot \left(x - w_j(t)\right) \tag{6}$$

The SOM model was a hexagonal map of 10 × 10, with 1000 training iterations and an initial learning rate of 0.5, which is decreased over time. It used a Gaussian neighborhood function. Weights were randomly initialized. The evaluation metrics show a Quantization Error of 0.083 and a Topographic Error of 0.021, which mean that the clustering and the topology preservation were effective.

3.6 Model–Concept Protocol Structure

In the study, the Model–Concept Protocol (MCP) was employed to systematically analyze multimodal sensory data. The framework comprises three layers: conceptual expressions of participants related to space, sketches or visual representations, and the application layers for artificial intelligence and data mining methods (Fig. 1).

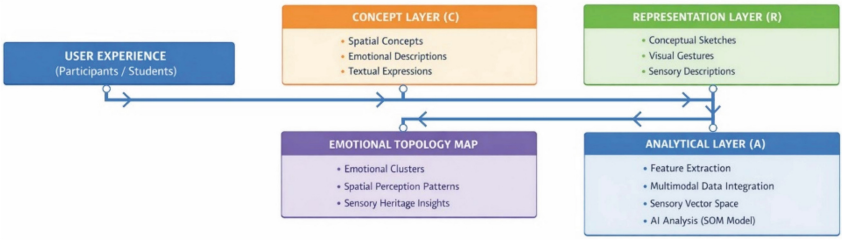


Fig. 1. Model-Concept Protocol Structure

4 Findings: Emotional Topology of the Bedesten

The analysis was done by the Self-Organizing Map (SOM) model to show the emotional clusters of the participants related to the Bedesten. Sensory and emotional perceptions are grouped around specific patterns based on participant experiences (Fig. 2). The sensory vector is computed using specific equations as X = [124, 30, 130, 155, 39 | 84, 13, 66, 64, 25]. The strongest sensory intensities are smell, touch and sight. Sum of sensory frequency was 478. The normalized sensory vector was calculated as Sn = [0.259, 0.063, 0.272, 0.324, 0.082]. Moreover, the total emotional frequency was calculated to be 252, which resulted in a normalized emotional vector En = [0.333, 0.052, 0.262, 0.254, 0.099]. The sensory-emotional topology of the SOM analysis is shown in further visualization in Fig. 2. Additional visualizations of the U-Matrix output and maps of neuron hit distribution in Appendix A (A1, A2, A3) increase the transparency of the method by visualizing the boundaries between clusters and the density of the data across the SOM structure (Fig. 3).

The Bedesten experience is one of touch, smell and sight with less emphasis on hearing and taste. The multimodal analysis on sensory data and sketches indicates a high correlation between senses and emotional responses with respect to the space. Tactile, visual and olfactory perceptions trigger emotions, showing a rich sensory environment created by stone textures and scents. The basic emotional concepts of "trace," "comfort,"



Fig. 2. Sensory Emotion Map

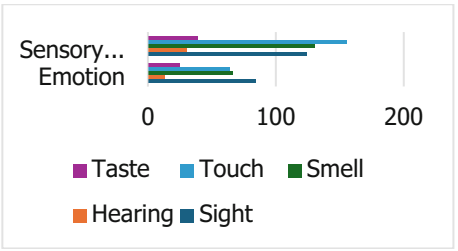


Fig. 3. Digitized sensory and emotions

"integration," "history," and "discovery" suggest that the Bedesten is an ambience that reinforces emotional links to the past. Our analysis with SOM shows the grouping of similar sensory-emotional patterns in the adjacent neurons, which indicates common perceptual experiences, and demonstrates the effectiveness of the SOM in mapping relationships in multimodal heritage data and recurring emotional patterns linked to the sensory features of the space (Fig. 4).

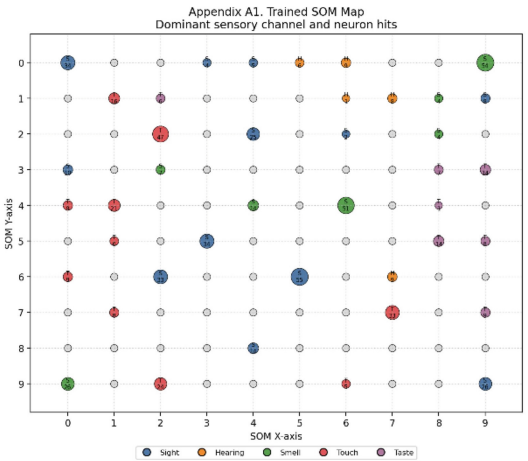


Fig. 4. Trained SOM Map

The U-Matrix visualization reveals the cluster structure of the dataset, showing the distance relationships between neighboring neurons. Areas of lower distances are groups of sensory-emotional observations with similar characteristics, and areas of higher distances are transitions between different perceptive groups. According to the description, the participants' experience is not identical, but is based on several main sensory-emotional themes. This is consistent with the idea of the Bedesten as a layered sensory heritage environment where different sensory channels trigger different emotional responses. The Hit Map shows the distribution of participant observations across the SOM neurons, indicating that some sensory-emotional patterns were commonly perceived by several participants. The clustering reveals the most salient topics in the

Bedesten environment and indicates the agreement among users about their perceptions of the space. On the other hand, neurons with a small number of hits correspond to unique or personal experiences. Taken together, the results confirm that the perception of sensory heritage in the Bedesten is the result of collective as well as individual experiences, reflecting the complex emotional engagement with historical urban environments (Fig. 5).

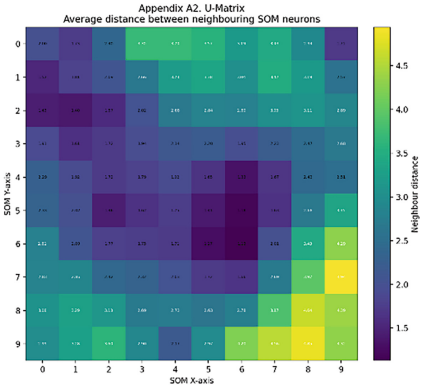


Fig. 5. U Matrix

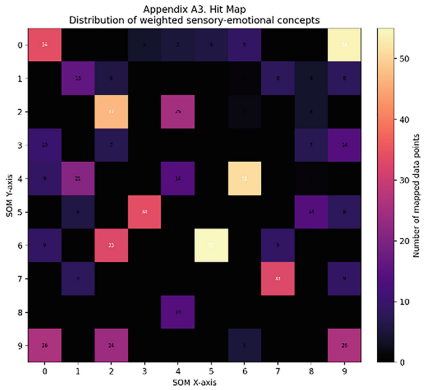


Fig. 6. Hit Map

The analysis of visual and concept sketches brings to light the role of sensory experiences and emotional responses in shaping user experiences, particularly in the context of the Bedesten. These conceptual sketches on the tactile and olfactory senses point to themes such as “trace,” “internalization,” and “comfort” where material texture and atmospheric qualities are of great importance. In this study, sensory frequencies were defined as sensory variables and conceptual expressions of participants were defined as emotional variables and evaluated by correlation analysis. The results indicate a significant relation between emotional responses and the senses of touch, smell and sight, which are identified as essential for the construction of spatial experiences. By contrast, hearing and taste were less correlated. The findings suggest that historical urban spaces, such as the Bedesten, do not only derive meaning from the visual architecture but also from the material textures and sensory atmospheres; therefore it is presented as a multilayered sensory heritage environment. A Pearson correlation analysis revealed moderate to strong positive correlations ($r = 0.61–0.83$, $p < 0.05$) between touch, smell and sight and the key emotional concepts of comfort and discovery. The correlation matrix also confirmed the central role of tactile, visual and olfactory perceptions in the emotional experiences of the Bedesten.

5 Discussion and Conclusions

We present the Model-Concept Protocol (MCP), a framework to organize sensory-emotional data from user experiences for artificial intelligence (AI) analysis. Using the Trabzon Bedesten as a case study, the framework leverages textual and sketch data produced by participants to build a multimodal representation of sensory interactions. The

main conclusions are that the sustainability of historical environments depends on the physical structures as well as their emotional atmospheres created by user experiences. The research calls for a methodological change in architectural and cultural heritage research through the lens of sensory heritage and emotional sustainability, allowing AI-supported documentation and experiential analysis. The MCP framework conceptualizes historical environments as dynamic emotional landscapes to help document sensory heritage, strengthen attachment to place, and guide adaptive reuse, thereby contributing to heritage continuity, cultural sustainability, circularity and United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities).

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Digitalisation Pathways for Circular Renovation and Energy Transition in the Built Environment

Gabriela Barbosa(✉) and Manuela Almeida

Department of Civil Engineering, University of Minho, ISISE, ARISE, Guimarães 4800-058, Portugal
id11912@alunos.uminho.pt

Abstract. Digitalisation is increasingly acknowledged as a critical enabler of the circular economy, supporting the shift from linear production models toward sustainable, closed-loop systems. While its implications for manufacturing and supply chains have been widely examined, its specific role in advancing the energy transition and strengthening the resilience of the built environment remains underexplored. The interaction between digital tools, circular strategies, and energy and material flows in buildings is particularly relevant given the sector's centrality to decarbonisation and climate-neutrality goals.

Emerging digital instruments, such as Digital Product Passports (DPPs), Building Renovation Passports (BRP), and Digital Building Logbooks (DBLs), provide lifecycle and product data to support circular practices, including resource efficiency, operational optimisation, and renovation planning. However, adoption is constrained by limited interoperability, fragmented data governance, and inconsistent policy frameworks.

This study conducts a comparative policy analysis of selected European digital policy initiatives, focusing on their relevance to circular renovation, integration with digital tools, and impact on energy performance. It provides a structured synthesis of policy instruments, a classification of digital tools, and a conceptual framework to assess alignment and fragmentation between policy objectives and implementation. The paper highlights interoperability challenges and outlines pathways to integrate digital infrastructures with renovation strategies to support EU energy transition goals.

Keywords: Digitalisation · Circular Economy · Energy Transition · Building Renovation Passport · Digital Building Logbook

1 Introduction

The building sector accounts for approximately 50% of resource extraction and consumption, over 30% of EU waste, 40% of energy use, and 36% of energy-related greenhouse gas emissions. Key materials such as cement, iron, and steel are major sources of emissions. Given this environmental footprint, transforming the sector is central to European climate and resource efficiency policies (Bragança et al. 2024).

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There is an urgent need to move beyond the linear "business-as-usual" model by applying circular economy (CE) principles to reduce resource consumption and lifecycle impacts (Executive Agency for Small and Medium sized Enterprises. et al. 2021).

The CE model promotes decarbonising the construction sector by reducing waste and resource extraction through narrowing, slowing, and closing resource loops (Çetin et al. 2021) (Keles et al. 2025). These approaches are increasingly seen as essential for a sustainable, low-carbon built environment (Sáez-de-Guinoa et al. 2022).

Despite growing policy focus, the links among EU frameworks, digital tools, and circular renovation remain underexplored.

This paper addresses this gap through a qualitative comparative policy analysis of European initiatives and a review of digital building information systems. Policy frameworks were selected based on relevance to circular economy objectives, integration with digital tools, and impact on energy performance. Digital tools were identified through a structured review of ScienceDirect (2022–2026), yielding 221 articles; after screening for relevance and scope, 52 studies were retained. The structured literature review informs the classification of digital tools presented in Sect. 2, which in turn provides the analytical basis for the comparative policy analysis. Together, these components feed into the proposed conceptual framework linking policy drivers, digital tools, and circular renovation practices. The study is positioned as a conceptual and policy analysis contribution, without primary empirical data.

2 EU Policy Frameworks Supporting Circular Renovation

The EU has introduced several policy initiatives that link circular-economy principles, sustainability, and digitalisation, collectively establishing a framework that connects circular-economy objectives to building renovation and data systems. However, their contributions differ significantly in regulatory strength, scope, and capacity to support digital and circular renovation practices. Frameworks were prioritised based on their binding regulatory force, explicit provisions for digital tools, and direct relevance to building renovation.

To strengthen the comparative analysis, policy frameworks were systematically assessed across six analytical dimensions: (i) scope, (ii) regulatory force, (iii) implementation maturity, (iv) level of integration with digital building tools, (v) interoperability provisions, and (vi) relevance to circular renovation. This framework enables a structured comparison of how different policies contribute to the digitalisation–circularity nexus in the built environment.

2.1 Comparative Overview of EU Policy Frameworks

The analysed policies reflect a multi-level governance structure spanning strategic, building-, and product-level instruments.

At the strategic level, the Circular Economy Action Plans (2015, 2020) define overarching objectives for resource efficiency and material circularity. However, as non-binding frameworks, they provide only indirect support for digitalisation and circular renovation.

Building-level policies show stronger implementation capacity. The Renovation Wave promotes large-scale renovation under the European Green Deal, emphasising lifecycle thinking and energy performance. The recast Energy Performance of Buildings Directive (EPBD) operationalises these objectives through binding requirements and supports digital tools such as DBLs and interoperable data systems, strengthening lifecycle data management.

At the product level, the revised Construction Products Regulation (CPR) introduces binding requirements for product transparency and sustainability, supporting structured digital information. In contrast, the Level(s) framework provides a voluntary methodology for lifecycle-based assessment, contributing to harmonisation but with limited direct impact.

Emerging initiatives, such as the EU Digital Building Logbook framework, aim to consolidate lifecycle data but remain under development with unresolved standardisation challenges (Hwang et al. 2025). Table 1 compares these frameworks across analytical dimensions, highlighting differences in regulatory strength, maturity, and capacity to support digitalisation and circular renovation.

Table 1. Key EU Policy Frameworks supporting Circular Economy

Policy	Scope	Regulatory Force	Implementation Maturity	Digital Integration	Interoperability Provisions	Relevance to Circular Renovation
Circular Economy Action Plan(2015, 2020)	Cross-sector	Strategic (non-binding)	High	Indirect	Limited	Indirect
Circular Economy Act	Cross-sector	Binding (expected)	Emerging	Moderate	Under development	Medium
Renovation Wave	Buildings	Strategic	Medium–High	Indirect	Limited	High
EPBD recast (2024)	Buildings	Binding (Directive)	High	Strong (DBLs, BRP, EPC)	Moderate	High
Level(s) Framework	Buildings	Voluntary	Medium	Indirect	Limited	Medium
CPR revision (2024)	Products	Binding (Regulation)	Medium	Moderate (DPP link)	Partial	Medium–High
EU Digital Building Logbook Initiative	Buildings	Emerging framework	Developing	Strong	Under development	High

The comparison shows that binding instruments, particularly the EPBD and CPR, play a central role in operationalising digital and circular objectives, while strategic and

voluntary frameworks provide direction but limited enforcement. This uneven distribution of regulatory force contributes to differences in implementation and impacts the effectiveness of digital tools across system levels.

2.2 From Policy to Practice: Digital Tools and System Integration

According to researchers (Antikainen et al. 2018) digitalisation accelerates the transition to a circular economy by closing material loops through precise product data and optimising processes to minimise waste and reduce transaction costs. These tools facilitate the exchange of building and product information across the lifecycle, enabling more informed renovation decisions and supporting circular construction practices.

The comparative analysis shows that policy frameworks operate at complementary system levels, shaping the development and deployment of digital tools throughout the building lifecycle.

At the building level, policies such as the EPBD and Renovation Wave enable tools including BIM, Digital Twins, DBLs, and BRPs. These tools support lifecycle data management, renovation planning, and performance optimisation. BIM enables structured digital modelling and circular design strategies, while Digital Twins extend these capabilities through real-time monitoring (Çetin et al. 2022; Hwang et al. 2025). DBLs function as central repositories that integrate materials, components, and renovation history, supporting informed, circular decision-making (Alonso et al. 2023).

At the product and material level, policies such as the CPR underpin DPPs and Material Passports, which provide structured data on product composition, environmental performance, and lifecycle characteristics. These tools enhance material transparency and traceability, enabling circular construction practices.

Table 2 summarises these tools and their contributions to circular economy and energy transition objectives, illustrating how policy frameworks are translated into operational digital mechanisms.

Despite their complementary roles, the integration of these tools across system levels remains limited. A functional division emerges in which building-level tools focus on energy performance and renovation planning, while product-level tools address material transparency. However, these domains are not fully aligned. DBLs are intended to centralise building information but depend on compatible product-level data, while DPPs provide detailed product information without clear integration pathways into building-level systems. This fragmentation limits the ability to connect material data with renovation decision-making processes.

Table 2. Digital tools' contribution to the circular economy.

Digital Tool	Description	Contribution to Circular Economy	Contribution to Energy Transition
Building Level Tools			
. digital modelling and operational tools			
Building Information Modelling (BIM)	Digital representation of the physical and functional characteristics of a building	Enables lifecycle material tracking, design for disassembly, and circular design strategies	Supports energy modelling, renovation planning, and building performance analysis
Digital Twins	Real-time digital replicas of physical buildings using sensor and operational data	Enable monitoring of building components and predictive maintenance, extending asset life	Optimise building operations and energy performance
. data repositories			
Digital Building Logbooks (DBL)	Digital repositories containing structured information about buildings across their lifecycle	Store information on materials, components, and renovation history, facilitating reuse and recycling	Integrate energy performance data and renovation pathways
. planning instruments			
Building Renovation Passports (BRP)	Long-term renovation roadmaps for individual buildings	Support stepwise renovation strategies that can incorporate circular construction principles together with DBLs	Guide energy renovation pathways towards highly efficient buildings
Material/ Product Level Tools			
. data repositories			
Digital Product Passport (DPP)	Digital record containing structured information about a product's composition, origin, environmental performance, and lifecycle characteristics	Improves material transparency and traceability, enabling repair, reuse, recycling, and secondary material markets	Provides data on product energy performance and lifecycle carbon emissions, supporting energy-efficient and low-carbon products
Material Passports	Databases documenting the composition and characteristics of materials used in buildings	Improve traceability of materials and enable reuse, recycling, and recovery at the end of life	Support lifecycle assessment and embodied carbon analysis

3 Policy, Digitalisation and Circular Renovation

The proposed framework builds on the policy and tool analysis in Sect. 2 as an original synthesis. Rather than depicting a linear link between policy drivers, digital tools, and renovation outcomes, it serves as a diagnostic structure for assessing their alignment. In particular, it helps identify mismatches between policy objectives, digital system development, and their practical application in circular renovation processes.

Figure 1 illustrates the conceptual framework linking European policy drivers, digital building information systems, and circular renovation practices. By improving data transparency and interoperability, these systems facilitate resource efficiency, material reuse, and energy performance optimisation, contributing to broader energy transition objectives. The framework is normative, proposing an integrated model derived from the policy and digital tool reviews in Sect. 2, making explicit the causal relationships between them.

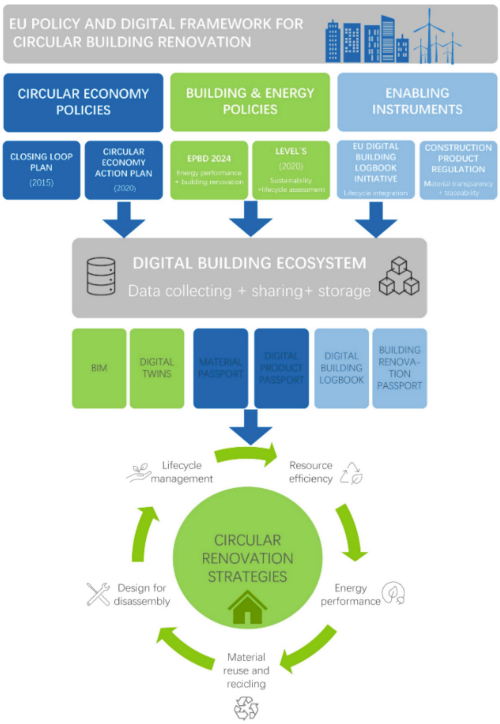


Fig. 1. EU Policy and Digital Framework for Circular Building Renovation, authors' own

The framework comprises three interconnected layers. The first, EU Policy Drivers, includes the Circular Economy Action Plans, the EPBD recast, the CPR revision, and the Renovation Wave, which define the mandates shaping the built environment. The second, Digital Enablers, encompasses the building- and product-level tools reviewed in Sect. 2 (BIM, Digital Twins, DBLs, BRPs, DPPs, and Material Passports), acting as the interface between policy objectives and renovation activities. The third, Circular Renovation Outcomes, includes key sustainability results such as resource efficiency, material traceability, improved energy performance, and reduced embodied carbon.

By structuring the interaction between policy, digital tools, and outcomes, the framework highlights that gaps in circular renovation are not only technological but systemic. Misalignments between building- and product-level policies lead to fragmented digital ecosystems, limiting the effectiveness of data-driven renovation strategies.

EU efforts to improve energy efficiency, circularity, and resource management support targets of a 55% reduction in greenhouse gas emissions by 2030 and climate neutrality by 2050. Achieving this transition requires systemic innovation, with digital tools enabling efficient processes and transparent access to product and resource data within integrated ecosystems (Cagno et al. 2021).

4 Discussion

The proposed framework contributes to the literature by integrating policy analysis and digital tool assessment within a single analytical structure. While previous studies have examined digitalisation as an enabler of the circular economy or analysed EU policy instruments for energy renovation (Hwang et al. 2025)limited attention has been given to how misalignments between these domains affect circular renovation outcomes. By explicitly linking policy levels with digital system functions, this framework provides a basis for identifying structural barriers to implementation.

The proposed framework integrates policy analysis and digital tool assessment within a unified structure, linking policy levels with digital system functions to identify structural barriers to circular renovation. Digital tools such as BIM, Digital Twins, Digital and Material Passports, DBLs, and BRPs support lifecycle data management and decision-making (Keles et al. 2025), their implementation remains fragmented due to limited interoperability, low digital maturity, and a lack of standardisation.

From the comparison between policy frameworks and tool functionalities, four key interoperability gaps emerge: (i) the absence of a common data schema linking BIM outputs to DBL repositories, reflecting fragmentation between modelling tools and data storage systems; (ii) the separation of DPPs and Material Passports under distinct regulatory tracks, limiting integration; (iii) the lack of standardised data exchange formats for BRPs across Member States, indicating uneven implementation maturity; and (iv) the absence of defined integration pathways between Digital Twins and DBLs.

These gaps highlight misalignments between policy objectives and digital infrastructures, reinforcing the need for coordinated standardisation to support circularity and the energy transition of the built environment.

5 Conclusions

This paper examined the role of digitalisation in supporting the transition towards a circular and climate-neutral built environment, focusing on the interaction between EU policy frameworks and digital building information systems. The analysis shows that digital tools—such as BIM, Digital Twins, DBLs, BRPs, and DPPs—have strong potential to enhance lifecycle data management, material traceability, and performance monitoring, thereby supporting circular renovation processes.

However, the findings also indicate that, while policy support is evolving, it remains fragmented across governance levels and instruments, limiting effective implementation. Interoperability emerges as the central bottleneck, with persistent gaps in data standards, system integration, and coordination between tools and policy frameworks.

Addressing these challenges will require coordinated efforts in standardisation, digital infrastructure, and regulatory alignment to enable digital tools to effectively support circularity and the energy transition in the built environment

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Modelling Earth: Comparison of Material Models for Earthen Materials Using Finite Element Analysis

Johanna Baier[1](✉), Jamila Loutfi[2], Eric Wente[3], Katharina Pfahler[4], and Konstantin Nille-Hauf[5]

[1] Bundesanstalt für Materialforschung und -prüfung, Unter den Eichen 87, 12205 Berlin, Germany
johanna.baier@bam.de
[2] Berlin University of the Arts, Hardenbergstr. 33, 10623 Berlin, Germany
[3] Stuttgart Technical University of Applied Sciences, Schellingstr. 24, 70174 Stuttgart, Germany
[4] University of Applied Sciences Regensburg, Galgenbergstr. 30, 93053 Regensburg, Germany
[5] Biberach University of Applied Sciences, Karlstraße 6-11, 88400 Biberach, Germany

Abstract. Finite element (FE) simulations offer a scalable framework to explore parameter variations such as slenderness, confinement conditions, and loading scenarios that cannot be tested experimentally in a systematic or economically feasible manner. This study investigates the ability of several constitutive material models to approximate the uniaxial compressive behaviour of rammed earth (RE). Stress-strain curves from unconfined compression tests on cylindrical RE specimens serve as the basis for model calibration and validation. Two RE materials with distinctly different stiffness characteristics were chosen to assess whether the selected models can capture varying material behaviour. Material models commonly used in geotechnical and structural analysis, such as Drucker-Prager, Menetrey-William and Concrete Coupled Damage-Plasticity are implemented and compared across four FE software environments: ANSYS Workbench, COMSOL Multiphysics, SOFiSTiK, and PLAXIS. All investigated models successfully reproduced the compressive strength. The models implemented in ANSYS Workbench and COMSOL Multiphysics additionally provided a good approximation of the nonlinear material behaviour and the overall stiffness response.

Keywords: Earthen Materials · Finite Element Analysis · Material Models · Unconfined Compressive Strength Test · Numerical Approximation

1 Introduction

In recent years, earthen construction has experienced increasing standardisation. In Germany, a normative framework was developed for earthen blocks (DIN 18945 [1]) and the structural design of earthen masonry (DIN 18940 [2]). In addition, a design guideline for rammed earth walls is currently under development [3]. However, compared to

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conventional construction materials such as reinforced concrete, earthen materials still lack a comparable empirical foundation. To address this deficit efficiently, upcoming parameter studies must be strategically designed to minimise the required experimental effort while maximising knowledge gain. This requires the development and calibration of reliable and precise material models capable of accurately reproducing the mechanical behaviour of earthen materials. Robust numerical models enable virtual testing, support the targeted planning of laboratory campaigns, and ultimately contribute to establishing earth as a dependable material for load-bearing structural applications.

As a first step towards this goal, this paper investigates the numerical modelling of the uniaxial load-bearing behaviour of unstabilised rammed earth (RE). Several constitutive material models commonly used in geotechnical and structural analysis such as Drucker-Prager (DP), and the Concrete Coupled Damage-Plasticity (CDP) model are implemented and compared across four finite element (FE) software environments. The study includes FE software used in both academic research (ANSYS Workbench [4], COMSOL Multiphysics [5]) and engineering practice (SOFiSTiK [6], PLAXIS [7]). The numerical simulations are calibrated and validated against experimental results from unconfined compressive strength tests on cylindrical rammed earth specimens.

2 Methodology

2.1 Basis for Numerical Studies - Unconfined Compressive Strength Tests

Two RE mixtures produced by different manufacturers were analysed, hereafter referred to as STL-1 and STL-2. The grain size distribution of both materials is reported in Baier et al. [3]. The manufacturing moisture content was set to 8.6 M-% for STL-1 and 8.1 M-% for STL-2, determined using the Drop Test defined in NZS 4298 [8]. Cylinders with a diameter d of 100 mm and a height H of 200 mm corresponding to an aspect ratio of $H/d = 2.0$ were chosen. Three specimens of each material were compacted using an automatic proctor machine and a compaction energy of 0.6 MJ/m^3. The material was placed in three layers. The specimens were dried under standard environmental conditions for mineral-based materials at 20 ± 2 °C and a relative humidity of 65 ± 5%. Mass equilibrium, defined as a maximum weight variation of 0.1 wt.-% within 24 h, was reached after four weeks. To achieve a uniform stress distribution during testing, the specimen surfaces were levelled using a 2–5 mm layer of gypsum.

The unconfined compression tests were conducted on a hydraulic testing machine at a constant displacement rate of 1.5 mm/min. In accordance with DIN 18945 [1], failure occurred within 30–90 s. Axial strain was recorded using three clip-on extensometers with a gauge length of 100 mm (see Fig. 1). The strain gauges were positioned in the mid-section of the test specimen to minimise the effect of lateral constraint.

The stress-strain curves, compressive strength f_c, ultimate strength f_u, and corresponding strains ε_c, ε_u are presented in Fig. 1. A linear elastic material behaviour up to $f_c/3$ was assumed, and the Young's modulus E_{33} was derived as secant modulus from the stress-strain curve. Although the grain size distributions of the two mixtures are quite similar, f_c and E_{33} differ. STL-2 exhibits lower stiffness than STL-1, with E_{33}/f_c

ratios of 424 and 1095, respectively. Both materials are therefore included in the numerical simulations, allowing the ability of the selected models to capture varying stiffness characteristics to be assessed.

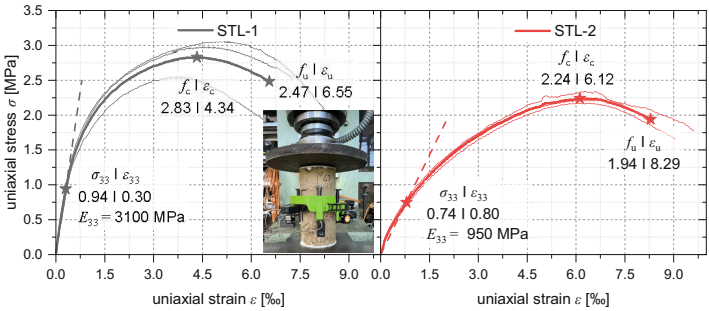


Fig. 1. Stress-strain curves of STL-1 and STL-2 including a picture of the experimental set up – thin curves represent measurements, thick curves the mean value.

2.2 Numerical Approach

To ensure comparability between different modelling environments, all FE programs were first benchmarked using a linear-elastic material model. Identical geometry, boundary conditions, loading scheme, and discretisation were applied in all software environments. No significant deviations in the resulting stress-strain response were observed, confirming numerical consistency.

The specimen was idealised as a cube with an edge length of 100 mm. The height corresponds to the experimental gauge length, enabling direct comparison of axial strain between numerical and experimental results. Stress was computed as the sum of vertical reaction forces divided by the cross-sectional area. Strain was computed from the displacement w_z of the top surface divided by the model height. To isolate constitutive effects and minimise computational cost, simulations were primarily performed using a single solid element. Large-deformation formulations were activated in all programs. In addition, a conventionally discretised mesh was analysed and subjected to a classical mesh convergence study. As both approaches produced identical stress-strain responses, the single-element model was adopted for subsequent parameter studies. A scheme of the mechanical model, including support (u_z, u_x, u_y) and displacement w_z, is shown in Fig. 2. The elastic behaviour was defined by the Young's modulus E_{33} reported in Fig. 1 and a Poisson's ratio of $\nu = 0.1$ according to [9].

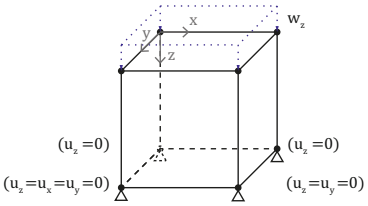


Fig. 2. Modelled load and support scheme of single solid element.

3 Results

3.1 Comparison of Numerical and Experimental Stress-Strain Curves

The numerical derived stress-strain curves are compared with the experimental results in Fig. 3. The following sections briefly describe the material models implemented in the respective FE software including input parameters and a brief evaluation. Where appropriate, deviations between experimental and numerical results were assessed using the Root Mean Square Error (RMSE).

3.2 ANSYS

Within the scope of this study, three different nonlinear material modelling approaches were evaluated using ANSYS Workbench [4]: Menetrey-Willam (MW) according to [10, 11], Drucker-Prager Concrete (DP-HSD) based on [12], as well as a Multilinear (ML) approach, where multiple stress-strain points from the test data were implemented. For the MW and the DP-HSD material model, a linear softening law was introduced. Elastic behaviour was assumed up to $f_c/3$. Beyond this threshold, plasticity was activated according to the respective constitutive material formulation. The input parameters of the material models MW and DP-HSD are listed in Table 1. The material models DP-HSD and MW offer the advantage that many of the required parameters can be derived directly from the experimental stress-strain curves. (Fig. 1). The tensile strength f_t was approximated based on results by [13]. The biaxial compressive strength f_{bc} was set in line with [14]. The material models require the input of plastic strain ε_{pl} rather than total strain ε when defining nonlinear material behaviour. The plastic strain ε_{pl} can be calculated using Eq. (1).

$$\varepsilon_{pl,i} = \varepsilon_i - \varepsilon_{el,i} = \varepsilon_i - \frac{\sigma_i}{E_{33}} \tag{1}$$

As shown in Fig. 3, both MW and DP-HSD result in a very good approximation of the experimental data of both RE mixtures with RMSE ≤ 0.05. The MW formulation showed slightly better convergence behaviour in the post peak area.

The ML material model demonstrates that the material behaviour up to f_c can also be approximated purely based on the experimental stress-strain relationship without a physically motivated constitutive formulation. For simple numerical analyses, such an approach may already provide a sufficient representation of the material response.

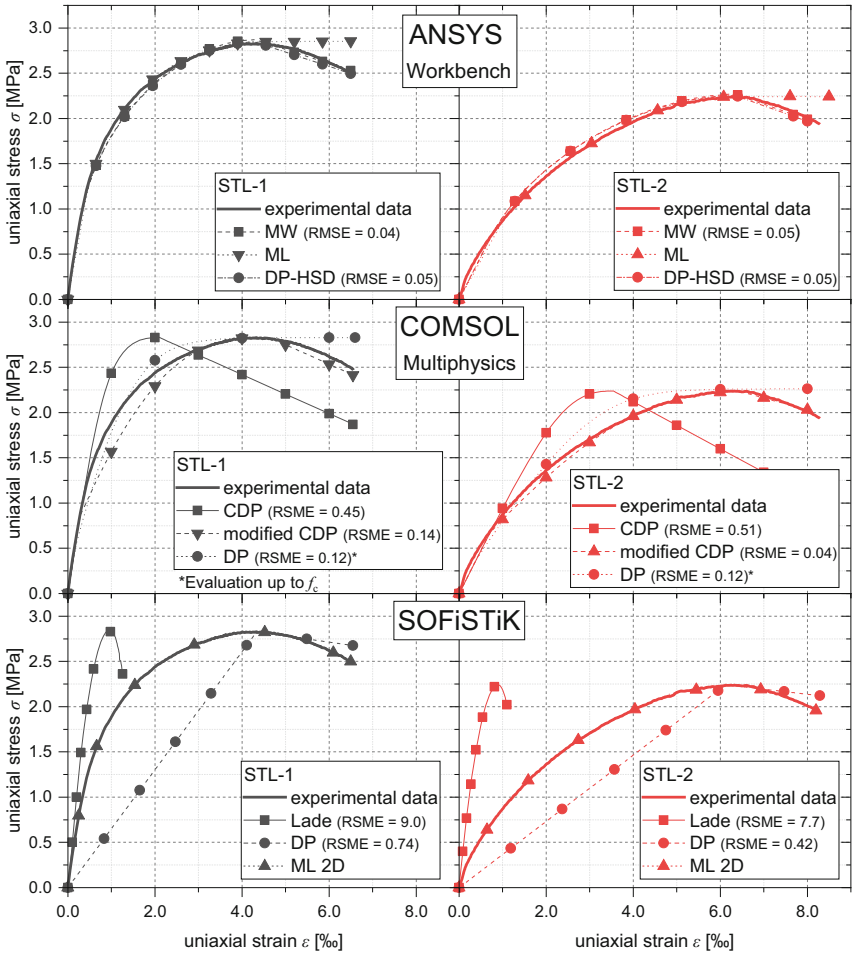


Fig. 3. Comparison of numerical and experimental stress-strain curves using the following material models: Menetrey-William (MW), Drucker-Prager (DP-HSD & DP), Concrete Coupled Damage-Plasticity (CDP), Lade and Multilinear (ML) approach.

Table 1. ANSYS [4]: parameter sets for material models MW and DP-HSD

f_c	f_u	$\varepsilon_{pl,c}$	$\varepsilon_{pl,u}$	f_{bc}	f_t	ε_t	$\sigma_{t,u}/f_t$	dilatancy
see Fig. 1 & Eq. (1)				$1.2 \cdot f_c$	$0.11 \cdot f_c$	3‰	1%	MW: $\psi = 30°$
								DP: $\delta_t = \delta_c = 1.0$

3.3 COMSOL Multiphysics

Two material models were chosen for the aim of this study: Soil plasticity model with Drucker-Prager (DP) criterion [12] and Concrete Coupled Damage-Plasticity (CDP) [15,

16]. The fitted parameters are listed in Table 2, and the resulting stress-strain curves are plotted in Fig. 3. For the DP material model based on the material parameters initial cohesion c_0, the friction angle φ and the dilatation angle ψ, the following hardening function with relation to the equivalent plastic strain ε_{pe} is proposed:

$$c_h = c_0 \cdot \left(1 + \varepsilon_{pe}\right) + 10 \cdot c_0 \cdot \left(1 - e^{-1000 \cdot \varepsilon_{pe}}\right) \tag{2}$$

For the CDP model, the compressive strength f_c was taken from the experimental evaluation (see Fig. 1). Furthermore, the default settings $1.13 \cdot f_c$ and $0.3 \cdot f_c$ were used for the biaxial compressive strength f_{bc} and the compressive yield stress σ_{cy}, respectively. For the post-peak behaviour, a dependency of the compressive fracture energy from the strain limit ε_{fc} was chosen. The CDP model was initially modelled using the default hardening parameters defined by [15]. In a second step, the hardening parameters were calibrated based on the stress-strain response (modified CDP).

All three material models successfully represent the uniaxial compressive strength. The upper limit for linear elastic response of both CDP models corresponds approximately to σ_{33}, whereas in the DP model the plastic response starts earlier due to c_0 and φ. Compared to the CDP, the modified CDP and the DP simulate the uniaxial material behaviour much better. Particularly, the modified CDP provides a good approximation of ε_c. Since no softening response has been added to the DP model, only the modified CDP shows satisfactory results for the post-peak behaviour.

Table 2. COMSOL [5]: parameter sets (STL-1 | STL-2) for material models DP and CDP.

DP	c_0 [kPa]	φ [°]	ψ [°]		
	68 | 60	30 | 25	30 | 25		
CDP	ε_{fc} [mm/mm]	H_p	A_h	B_h	C_h
	1E-4	0.01	0.08	0.003	2
Modified CDP	1E-4 | 1.75E-4	0.001 | 0.08	0.0065 | 0.007	0.006 | 0.0065	0.2

3.4 SOFiSTiK

Within the scope of this study, two elastoplastic constitutive models were employed for simulations using a single solid element: the Drucker-Prager (DP) model based on [12] and the Lade model according to [17]. For the implementation of the DP model a friction angle $\boldsymbol{\varphi}$ of 30° was assumed. The cohesion $\boldsymbol{c}$ was determined according to [18] using Eq. 3. However, nonlinear hardening or softening behaviour is not explicitly considered in the material model. Therefore, the secant modulus E at the compressive strength was adopted instead of the experimentally determined Young's modulus E_{33}. This allows the modelling approach to reproduce f_c and ε_c correctly.

$$f_c = 2 \cdot c \cdot \tan\left(45 + \varphi/2\right) \tag{3}$$

The modelling approach according to Lade [17] uses a three-dimensional failure criterion that was proposed for soils. The formulation involves only three independent material parameters and is expressed in terms of the first and third stress invariants of the stress tensor. For the implementation in SOFiSTiK [6], the input parameters were determined according to the equations provided in [17]. To activate the nonlinear material behaviour within the model, the experimentally determined Young's modulus E_{33} had to be intentionally overestimated**.** Consequently, although the model reproduces the compressive strength and exhibits a nonlinear stress-strain response, the overall stiffness is significantly higher than observed in the experimental data. Additionally, a two-dimensional single plane element with a multilinear stress-strain curve (ML 2D) was investigated, using several stress-strain points from the test data. In analogy to the modelling approach used for the solid element, the single plane element was supported without additional constraints to avoid unintended boundary effects. For simple two-dimensional applications, this approach can adequately represent the material behaviour (Table 3).

Table 3. SOFiSTiK [6]**:** parameter sets (STL-1 | STL-2) for material models DP and Lade.

DP	E	ν	f_t	$\varepsilon_{pl,u}$	φ	φ_u	c	c_u	ψ
	652 | 366 MPa	s. section 2.2 & 3.1			30°		816 | 647 MPa	713 | 560 MPa	0°
Lade	E	ν	f_t		η_1		η_2	m	
	5000 MPa	s. section 2.2 & 3.1			5391 | 4282		$0.1 \cdot \eta_1$	1.0	

3.5 PLAXIS

The modelling approach described in Sect. 2.2 could not be implemented in PLAXIS [7]. Therefore, no comparison is provided here. However, PLAXIS [7] offers an option for calibrating material models using the integrated "SoilTest" tool. This tool allows to calibrate a selected material based on various experimental data, such as uniaxial, triaxial, oedometer tests and others. Against this background, PLAXIS [7] should still be considered as an option for FE analyses of earthen construction elements.

4 Discussion and Conclusion

In this study, several material models implemented in different FE software environments were applied to numerically reproduce the stress-strain curves of two RE materials obtained from uniaxial compression tests. Where possible, input parameters were derived from the experimental data; otherwise, they were assumed based on literature or fitted. Deviations between numerically and experimentally determined stress-strain curves were quantified using the Root Mean Square Error (RMSE).

In ANSYS Workbench [4], all selected material models yielded a very good approximation for both materials (RMSE ≤ 0.05), with most input parameters derivable directly from the experimental data without calibration.

In COMSOL Multiphysics [5], the DP model provided a good approximation of the material behaviour up to f_c (RMSE $= 0.12$), while requiring significantly different input parameters compared to ANSYS. The CDP model likewise resulted in a satisfactory approximation of the material behaviour, upon modification of the internally defined hardening parameters (RMSE of 0.14 for STL-1 and 0.04 for STL-2).

In SOFISTIK [6], a two-dimensional ML approach analogous to that used in ANSYS enabled a perfect approximation of the stress-strain curve. In the three-dimensional model, the compressive strength f_c was well reproduced by the selected material models. However, the DP model was limited in capturing the nonlinear material behaviour, and the calibrated parameters for the Lade model overestimated the stiffness of RE.

In PLAXIS [7], the intended modelling approach could not be implemented. However, the integrated calibration tool "SoilTest" offers a promising option for future FE analyses of earthen construction elements.

In summary, all investigated material models were able to reproduce the compressive strength f_c. The models implemented in ANSYS Workbench and COMSOL Multiphysics additionally captured the nonlinear material behaviour and overall stiffness response, demonstrating their suitability for approximating the uniaxial compressive behaviour of RE. However, since parameter sets were derived solely from uniaxial compression tests, the results cannot be considered generally applicable. Further tests are required to validate lateral deformation (ν) and volumetric (ψ) behaviour and to extend models to multiaxial stress states. The findings should therefore be understood as an indication of the approximation quality achievable with the selected models and the available test data, rather than a conclusive assessment of their general suitability.

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Author Contributions J. Baier and K. Nille-Hauf evaluated the numerical model in ANSYS Workbench, J. Loutfi in COMSOL Multiphysics, E. Wente in SOFiSTiK, and K. Pfahler in PLAXIS.

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Compatibility Review of Publicly Available Experimental Data on Common Building Material Temperature Dependent Properties for use with ML Algorithms

Iasonas Bakas[1(✉)], Karolos J. Kontoleon[1], Eleftherios K. Anastasiou[1], Georgios Are-toulis[1], and Müslüm Arıcı[2]

[1] Department of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece
iasompak@civil.auth.gr

[2] Mechanical Engineering Department, Engineering Faculty, Kocaeli University, Kocaeli, Turkey

Abstract. The analysis and predictive capabilities of Machine Learning (ML) algorithms are becoming an increasingly invaluable asset in the research domains of heat transfer and building materials. Precision and high performance of such models are heavily reliant on the availability of substantial amounts of data for training and testing purposes. This study concentrates on reviewing available sources of experimental data and assesses compatibility implications with ML algorithm requirements. Focus is given on common building materials with temperature-dependent properties assessed against elevated temperatures or fire scenarios. The structure and consistency of the available information are discussed and compared with the fundamental training data requirements of ML algorithms, focusing on Artificial Neural Networks. The study concludes with a brief discussion on the financial and environmental benefits of data and material circularity and proposes methods of reusing available experimental results in cutting-edge Artificial Intelligence applications.

Keywords: building materials · data analysis · machine learning · information circularity

1 Introduction

1.1 Machine Learning as a Tool for Scientific Research

Machine Learning (ML), under the wider sphere of Artificial Intelligence (AI), is evolving into a valuable tool in scientific research, commercial production and industrial applications. It enables deeper understanding of data, reveals interconnections, supplements or surpasses the capabilities of existing statistical methods of analysis and creates opportunities for circularity and sustainable research and production.

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Fully utilising the potential of such innovative tools relies on understanding and compliance with certain requirements. The algorithm architecture and choice of hyper-parameters are integral to developing a functional and effective model. The reliability and completeness of training and test data are fundamental to ensure underlying information patterns are captured with high levels of precision and confidence. Inherent biases by the model developers need to be filtered and isolated, while accessibility to the end user is essential to ensure uptake of the proposed models and their beneficial features.

This study focuses on the aspect of data availability and quality for training effective ML models. It outlines issues of available datasets, through the prism of building material properties, heat transfer and fire science. It discusses the opportunities created by ML in relation to information circularity and experimental data reuse and invites dialogue on approaches to enhance data depositories and accessibility of information.

1.2 Scientific Knowledge and Data Circularity

Circular Economy (CE) and its ability to "close the loop" on production processes is receiving notable attention due to striking a comfortable balance between economy, societal requirements and environmental consciousness [1]. Machine Learning is already contributing to the development of CE and it is suggested that reverse engineering the principles of circularity to advance ML itself is worth exploring [2]. The current mindset of singularity in information production/consumption is discouraging data sharing, reuse and leads to "fragmentation and lack of interoperability" in the heavily data-reliant field of Machine Learning [3].

Two aspects exacerbate the current difficulty in reusing scientific data in the context of information circularity and subsequently advancing ML. A lack of consistent methodology on recording how and with what purpose in mind datasets have been created hinders future attempts to access and reuse the stored information [4]. Secondly, the infrastructure that facilitates information circularity (at least in the context of reusing scientific data) needs to be enhanced. Data is currently stored in multiple decentralised repositories, behind varying types of access restrictions, making reuse either by researchers or automated information trawlers impractical [5]. Steps to alleviate the situation are being taken, in the form of official guidelines being drawn up (the European AI Act and the AI Right of Bills, for example). Further suggestions involve clearer guidance on data structuring and coherence by scientific journal publishers ahead of publication acceptance and clearer descriptions of dataset features and limitations by researchers who obtain the data in the first place, as well as more descriptive metadata and guidance both for discoverability by machines and organisation by annotator and editorial teams [6]. The core principles of data circularity and reuse are listed on Table 1.

Table 1. Information and data circularity requirements [5].

Requirement	Practical benefit
Findable	Adequately detailed and accurately labelled meta-data logged on a "searchable" depository to enable human or machine searchers to identify the required dataset.

(*continued*)

Table 1. (*continued*)

Requirement	Practical benefit
Accessible	Once found, the data should be easily accessible for free, through a universally accepted protocol.
Interoperable	Once retrieved, data should be in a universally acceptable "knowledge representation" format, including cross-referencing to other meta-data as required.
Reusable	Data being traceable to its source, with detailed descriptions of content, usage permissions and in line with universally accepted standards for the corresponding domain.

1.3 Scope and Contribution of This Study

The aim of the study is to identify representative sources of available experimental results that can be used for training ML algorithms while discussing opportunities on information circularity. It reviews previously published studies in the field of common building material properties exposed to fire and elevated temperatures, with special focus on concrete applications. This study also assesses the compatibility of such data against the fundamental training requirements of ML algorithms, focusing on Artificial Neural Networks (ANNs). This review is not exhaustive, and it concentrates on the most recent or representative publications available on online indexing platforms.

2 Methodology

The adopted research methodology follows the principles of meta-narrative literature review. The cornerstones of meta-narrative research comprise the initial research question setting; establishing the scoping and search strategy; a method of quality appraisal and data extraction; and finally, the stage of information analysis and narrative synthesis The initial paper selection process involved keyword and title review. Further filtering relied on assessment of abstract relevance, clarity and reproducibility of proposed methodology and finally relevance of conclusions [7].

The research objective for this work is distilled in the following question: "What are the features of the available experimental data of temperature-dependent material properties that can be used for training ANN models predicting thermal behaviour of building elements exposed to fire?". Parallel topics such as ML training data requirements and circularity of existing scientific knowledge are woven into the narrative by reviewing and discussing relevant scientific publications.

The scope of this study has been identified in previous paragraphs. The search strategy utilises online indexing platforms such as Scopus, IEEE, Google Scholar and Web of Science. Combinations of keywords such as "material properties, thermal behaviour, temperature-dependent properties, concrete, elevated temperatures, data circularity, Machine Learning data requirements" were used. The returned results were screened on their relevance and quality before including in the below review.

3 Results

3.1 Experimental Data Availability and Quality

A considerable volume of experimental and analytical research exists in relation to concrete temperature dependent properties when exposed to elevated temperatures [8]. For the purposes of this study 15 published papers have been selected and reviewed in detail. These feature both useful experimental results but also encourage discussion in relation to scientific knowledge and data circularity.

Studies have been focusing on different aspects and parameters of concrete specimen thermal behaviour. The impact of age, in conjunction with the concrete mix characteristics, and environmental conditions was investigated for temperatures up to 60 °C with a Japan developed tester for thermal conductivity [9]. Similarly, an electrical furnace was used to investigate the impact of aggregate type to the thermal conductivity and volumetric change of concrete when exposed to temperatures up to 600 °C [10]. Focusing on the impact of by-product admixtures, the hot wire method was utilised, for heating lightweight concrete specimens to 900 °C [11]. On the other hand, despite adequate details being provided for the fiber content and coarse aggregate mix design of samples, the experimental investigation scope varies considerably from being limited to 25 °C in one instance to extending to 1000 °C in others [12–15]. The experiment time (250 min) is reported only in one investigation of thermal behaviour of fly ash-based concrete for temperatures up to 550 °C with readings at 100 °C intervals [16]. Other studies focus on numerical investigation of cracked concrete or mixes containing asphalt, using experiments for validation but providing nominal information on temperatures developed or time required for the experiment [17, 18]. Although various numerical formulas are provided to describe the development of thermal conductivity, no experimental data is made available on any of the above studies.

A smaller proportion of studies (26% of the reviewed work) mention that experimental data can be made available upon specific request. Different experimental approaches were used to measure the thermal conductivity and specific heat of three samples of lightweight concrete at temperatures ranging from 20 to 1000 °C [19]. Others focused on the impact of fiber content in ultra-high-performance concrete, reviewing the thermal conductivity of samples at temperatures up to 850 °C [20]. The thermal conductivity, specific heat and thermal expansion of sleeving grout was subject of experimental investigation for temperatures up to 900 °C [21]. The influence of water content and levels of saturation were also reviewed analytically and experimentally for concrete samples heated up to 800 °C [22].

The compatibility and structure of the experimental data obtained through these works would need to be assessed against the fundamental requirements of Machine Learning models.

3.2 Machine Learning and Training Data Requirements

As seen in the previous paragraphs, experimental data on the temperature dependent material properties does exist. However, it is essential that the process of obtaining,

managing and preprocessing this data is assessed, before analysing and hopefully extracting useful conclusions [23]. The reason for such upfront scrutiny is that the quality of obtained information is detrimental to the quality of the ANN model predictions. Ensuring the provided training data is complete, balanced and accurate (both in terms of recorded features and target figures accuracy) is critical for the efficient operation of an ML model [24]. Gaps in the obtained data (either due to randomly missed/mistakenly noted observations, due to systematic recording errors or corruption in the process of storing, retrieving or preprocessing) can skew or significantly mislead the predictions made by an ANN [25, 26]. The presence of noisy data in the training dataset can be similarly impactful. Apart from potential degradation of predictive capabilities, noisy data elevates the complexity of the model leading to increased training times and computational costs [27]. Depending on the application, data of appropriate quality would conform with the criteria listed on Table 2.

Table 2. Machine Learning training and test data requirements.

Requirement	Qualitative explanation	Impact on Machine Learning model
Completeness	Data should not contain: • observations/entries with missing values. • features with missing titles or labels.	Missing observation values can create imbalances in the training data, affecting the quality of the ML predictions. Missing feature labels can lead to unexpected predictions due to erroneous consideration of training data sections.
Balance	A balanced amount of data should be available to represent each class or feature.	Unbalanced volumes of data lead to misrepresentation of data classes affecting the accuracy of the model.
Accuracy	Data should be free from systematic erroneous entries, noisy recordings and systematic outliers.	Although ML can quantify and filter out the impact of outliers, systematically erroneously recorded data, or noisy readings can skew the final predictions of the model. Such data also increases complexity of the model and reduces its predictive efficiency.
Consistency	Data entries should be presented consistently, avoiding variations in spelling, abbreviations, different languages, synonyms etc.	Data presentation inconsistencies can lead to unexpected editing results in the pre-processing phase and could create multiple data categories referring to the same entries or entry categories.
Volume	Adequate quantity of data should be available.	Scarcity of data could lead to unstable ML models, limited range of application or unreliable predictions [28].

Considering the influence of data quality on ML performance, this initial quality assessment should be tailored to the needs of the specific application. Different models have different requirements and tolerance towards quantity and quality of training data [24]. Regression is an example where data scarcity can lead to overfitting or model imbalances. When the available training data is riddled with the above weaknesses, strong domain prior knowledge is essential to understand, assess, interpret and accept or reconsider the generated ANN predictions [29]. A structured regime of recording data, ensuring quality criteria are met at the outset, could mitigate the risks of over recording (increased time, upfront costs) or under recording (data scarcity, noise, missing or skewed data or delays and associated data re-collection costs) [30].

4 Conclusions

This study concentrated on the implications of data availability and circularity when attempting to develop ML models predicting the thermal behaviour of concrete exposed to elevated temperatures. Developing these models necessitates a substantial amount of tabulated data. To ensure functionality, efficiency and reliability of the ML model, the data needs to be consistent, complete and balanced.

A significant number of experimental studies exist, reporting on the thermal behaviour of concrete exposed to fire or elevated temperatures. They report notable results and observations through schematics, diagrams and mathematical models.

However, this wealth of information and data is generally inaccessible for further use in Machine Learning research. The datasets are unavailable or difficult to access. There is also high variation in how and what data is recorded, necessitating convoluted pre-processing, performance or scope compromise or even rendering the intended research not possible.

It becomes apparent that action is needed to ensure that existing scientific knowledge becomes reusable in the context of building fire design and Machine Learning development. Possible actions would include, but not be limited to:

- Develop data sharing and storing protocols for fire testing results.
- Establish publicly available datasets drawing information from real time data collection sensors in existing buildings or lab experiments.
- Standardise the way data is recorded, labelled and enriched with meta-data.
- Obtain feedback through reviewing current fire research community needs and align data recording, reporting and sharing accordingly.

Considering that ML and AI in general are becoming indispensable tools in research, a general mindset shift might be necessary, where data curation and circulation become deliverables on their own. Future research could focus on preprocessing specific datasets, assessing existing knowledge gaps and establishing methodologies for effective use of existing knowledge. Standardinsing methods for tackling said gaps with bootstrapping techniques, FE modelling, and crossover review of existing experimental sets would be another essential future research avenue.

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From Materials to Cities: Understanding Cross-Scale Challenges Affecting Urban Material Flows

Adriana Salles[1(✉)], Marianna Marchesi[2], Raluca Buzatu[3], and Luís Bragança[1]

[1] ISISE, ARISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal
adriana@civil.uminho.pt
[2] Welsh School of Architecture, Cardiff University, Bute Building, Cardiff, UK
[3] Politehnica University Timisoara, Faculty of Civil Engineering, Timisoara, Romania

Abstract. By promoting a regenerative approach, the Circular Economy has been seen as a pathway to sustainable urban development. As a key component of urban circularity, urban metabolism examines the flows and stocks of resources within cities, including materials and energy. Increasingly, cities are applying this approach within a circular framework to identify opportunities to reduce resource dependence, improve efficiency, and guide more sustainable urban development. However, analyzing materials flows at the city level poses numerous challenges, including technical ones. Among the different categories of technical challenges, the lack of information/data is a relevant one. Understanding the correlations between this challenge at the urban level and challenges at the material and building scales is essential for identifying effective solutions to overcome them.

This study investigates how technical challenges, at the material and building levels, influence the analysis of material flows, particularly in terms of information and data, in urban systems. Furthermore, it explores how digital technologies, namely BIM and GIS, can be enablers and drivers to overcome these challenges. To this end, a desk research approach is employed to detect and map correlations between cross-level technical challenges in the built environment and to identify how digital technologies have been used to overcome the challenges. Finally, based on findings, a conceptual framework is proposed that identifies the use of BIM and GIS at the material and building levels to overcome technical challenges and how these results can be applied to material flow analysis at the urban level.

Keywords: Technical Challenges · Circular Economy · Urban Systems · BIM · GIS · Circular Strategies

1 Introduction

The transition towards circular and sustainable cities has intensified global interest in understanding the resource dynamics within the urban built environment. In this context, the Circular Economy (CE) has emerged as a central policy and research paradigm, advocating for regenerative cycles that minimize waste, retain material value, and decouple urban development from primary resource extraction [1].

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Urban Metabolism (UM) constitutes a structural analytical lens through which cities can be examined as systems that consume inputs, including materials, energy, water, and food, and generate outputs in the form of products, waste, and emissions [2]. Among the different methods to analyze the metabolism of cities, Material Flow Analysis (MFA) enables systematic accounting of material inputs, stocks, and outputs within a defined urban system boundary, serving as a diagnostic tool for identifying material inefficiencies and monitoring progress towards circularity targets [3, 4]. Despite growing methodological advancements, the analysis of materials flows at the urban scale still faces technical challenges. Among these is the scarcity, fragmentation, and inconsistency of data describing material stocks and flows across different spatial and temporal scales [5]. These challenges are not isolated to the city scale but are deeply rooted in upstream deficiencies at the material and building levels, the scales at which the physical characterization of the built environment begins.

Digital technologies, particularly Building Information Modeling (BIM) and Geographic Information Systems (GIS), have been increasingly recognized as transformative enablers that bridge data gaps across scales [6]. Their integration represents a promising approach towards City Information Modeling (CIM), capable of supporting multi-scale urban data aggregation and analysis [6, 7]. However, barriers, including ontological misalignment, data granularity mismatches, and platform interoperability limitations, continue to impede their systematic use in urban MFA. This paper brings material, building, and urban scales information challenges into a single cross-scale framework and examines how BIM and GIS can support the upward translation of data needed for urban MFA.

2 Theoretical Background: Technical Challenges Across Scales

The built environment is characterized by an interconnected, scalable structure in which material properties, building components, and urban systems interact in complex, interdependent ways. Technical challenges manifest distinctly, yet correlatively, across these scales, with data and information deficiencies representing a critical cross-cutting constraint [8]. In this paper, the material scale refers to information associated with individual materials, products, and components, such as composition, technical properties, certification, traceability, and passport data. The building scale refers to information related to the aggregation, organization, and lifecycle tracking of those materials and components within assembled building artefacts, including stock indexing, as-built documentation, disassembly records, and building layers. The urban scale refers to information related to resource inputs, stocks, and outputs within defined urban boundaries. The distinction among scales is important because urban MFA depends not only on knowing what materials exist, but also on knowing where and how they are embedded within buildings.

Across the three scales of the built environment, lack of data and information constitutes one of the most persistent categories of technical challenges impeding CE implementation [8]. At the material scale, the most frequently reported barrier concerns data availability, accessibility, and accuracy, including unreliable data, outdated material passports, and limited information on salvaged components. These are followed by deficiencies in traceability and certification, which weaken the capacity to verify the quality

and performance of reused materials throughout the value chain. At the building scale, the challenge shifts from characterizing individual products to aggregating and tracking information in assembled artefacts. Key barriers include incomplete material stock indexing, absence of as-built documentation, insufficient tracking of reused materials across lifecycle phases, and lack of disassembly records. These limit the reuse of products elsewhere when buildings or components are dismantled. At the urban scale, barriers include limited data capabilities, insufficient integration across information sources, and restricted data availability for CE monitoring and planning [9]. Together, these challenges constrain the reliability, granularity, and temporal depth of urban MFA.

3 Methodology

This study adopts a desk-research approach grounded in a structured literature review and thematic synthesis. The analysis builds on previous review-oriented works addressing technical challenges to circular strategies in the built environment and the role of digital tools in supporting circularity and urban-scale material analysis [7, 8]. The first study [7], critically reviewed 19 papers, from a total of 75, from 2018 to 2025. By addressing the question: "*Is City Information Modeling currently defined and used in the context of Material Flow and Stock Analysis?*", the study aimed to understand the relationship between digital tools, namely City Information Modeling (CIM), and urban material analysis (MSA and MFA). The second study [8], on which this research is built, identifies and analyzes the primary technical barriers impeding the transition to a circular economy in the built environment, examining challenges across the urban, building, and material scales and exploring the potential of digitalization, design for disassembly, and BIM as enabling strategies to overcome them. The research approach of the present study was designed to: (i) identify and classify technical challenges related to data and information across the three scales; (ii) map correlations between challenges across scales in the lens of the analysis of the materials flows; and (iii) identify documented applications of BIM and GIS that respond to these challenges.

Building on these sources, the present paper conducted an interpretive cross-scale synthesis to propose a framework, constructed through iterative thematic synthesis, in which technical challenges were systematically mapped against documented applications of BIM and GIS technologies and organized into a hierarchical structure reflecting the scalar progression from material characterization to urban-level MFA. Challenge priorities were established based on frequency of mentions in the literature; they represent research relevance, not validated real-world priorities, and further validation is needed.

4 Cross-Scale Technical Challenges and Enablers in the Built Environment

Data and information deficiencies do not operate in isolation at each scale but exhibit a structural propagation pattern: gaps in material-level data, particularly regarding traceability, passport completeness, and quality documentation, cascade upward to constrain building-level material stock assessments, which in turn limit the reliability and resolution of urban-scale MFA inputs. This cross-scale propagation is further intensified

by the absence of standardized data schemas capable of ensuring semantic consistency across scales, a condition at the intersection of information deficiencies and the lack of technical standards that directly conditions the effectiveness of digital technology interventions. Similarly, at the urban scale, limited knowledge of UM methodologies and digital analytical tools constrains practitioners' capacity to deploy GIS-based platforms for spatiotemporal material flow mapping, even where underlying data are partially available. Table 1 maps these cross-scale correlations.

These literature-derived correlations indicate the principal points at which BIM and GIS may act as cross-scale enablers: at the material scale, through structured digital capture of material properties and passport data; at the building scale, through interoperable BIM models aggregating component-level information; and at the urban scale, through GIS-based platforms integrating building stock data for city-level flow analysis. As enablers, BIM and GIS address different but complementary dimensions of the cross-scale information problem: BIM supports structured representation and lifecycle tracking of materials and components, whereas GIS supports spatial aggregation, territorial analysis, and urban-scale interpretation.

At the material scale, BIM-based material passports offer a structured mechanism for encoding and updating material properties throughout the building lifecycle, directly addressing the data availability and traceability deficiencies. At the building scale, existing BIM models have been applied for material stock and material intensity assessment [9, 10], deconstruction planning, and selective demolition, supporting end-of-life material recovery and reuse strategies [11, 12]. At the urban scale, GIS has been extensively applied to address deficiencies in spatial resolution and temporal coverage. Applications include hotspot analysis to identify spatial concentrations of building material stocks, 4D GIS models to characterize urban building metabolism and construction and demolition waste flows, and integrated GIS–MFA–LCA frameworks to analyze the spatiotemporal dynamics of building stocks [13]. These studies collectively establish GIS as the primary tool for spatially aggregating and analyzing distributed material data at the city level, directly responding to the data integration and accessibility barriers identified at the urban scale.

The integration of BIM and GIS represents the most direct technological response to the cross-scale data propagation problem. Parezanović et al. (2025) [9] combined BIM models with GIS cadastral data to assess building material stocks, while Triantafyllidis et al. (2025) [10] demonstrated that linking georeferenced BIM models with GIS enhances spatial analysis capacities. The convergence of BIM and GIS capabilities through CIM frameworks represents a promising trajectory for cross-scale data integration. By enabling the translation of building-level material data into spatially referenced urban datasets, BIM–GIS integration holds the potential to substantially improve the granularity and consistency of urban MFA inputs [7]. An explicit articulation of this integration is proposed by Schiller et al. (2024) [6], who developed a materiality-based City Information Model (mCIM) applying MFA principles to construct a material cadastre map, positioning GIS as the urban-scale modeling framework and BIM as the source of detailed building-level material data.

Critically, the reviewed literature demonstrates that BIM and GIS are predominantly applied in isolation, with their integration remaining partial and rarely framed within a

Table 1. Cross-scale mapping of information/data technical challenges in the built environment.

Challenge/ category	Material Scale	Building Scale	Urban Scale
Data Availability and Accuracy	Unreliable material data; incomplete material passports; limited data on salvaged components	Lack of material stock indexing; absence of as-built documentation; inaccurate building component databases	Limited georeferenced building stock data; insufficient data for CE monitoring and planning
Traceability and Certification	Lack of certification for reused products; absence of component-level traceability across the value chain	Insufficient tracking of reused materials across lifecycle phases; absence of disassembly records	Limited provenance data for urban material flow attribution
Standardization	Absence of standardized material data schemas; incompatible material classification systems	Lack of open BIM data standards (e.g., IFC); inconsistent Level of Development (LOD) specifications	Absence of harmonized urban material accounting frameworks; incompatible spatial data standards
Spatial Resolution	Material-level spatial referencing largely absent; components not georeferenced	Building-level spatial data inconsistently captured; georeferencing dependent on GIS integration	Spatially inconsistent datasets; difficulty attributing material flows to specific urban zones or functions
Temporal Coverage	Limited longitudinal data on material performance and degradation over time	Lifecycle phase data fragmented; design-stage data rarely updated through construction and use phases	Temporally misaligned datasets; absence of dynamic stock inventories for urban monitoring
Interoperability	Incompatible material data formats; absence of machine-readable material passports	Lack of interoperability between BIM platforms; data exchange barriers across project stakeholders	Insufficient integration among urban data sources; limited BIM-to-GIS data translation capacity

Cross-scale propagation: data availability gaps cascade upward from material to building to urban scale, constraining MFA resolution at each level. Traceability gaps undermine flow accounting reliability. Absence of shared standards limits semantic interoperability. Spatial and temporal deficiencies at lower scales reduce disaggregation capacity in urban MFA.

unified cross-scale analytical structure [7]. This gap, compounded by the identified barriers to semantic interoperability and standardization, motivates the conceptual framework proposed in Sect. 5, which explicitly structures the roles of BIM and GIS across the material, building, and urban scales to support city-level MFA.

5 Proposed Conceptual Framework

The proposed conceptual framework explains how interventions at the material and building scales can improve the data foundations required for urban MFA, as shown in Fig. 1. The framework operates across three interdependent layers.

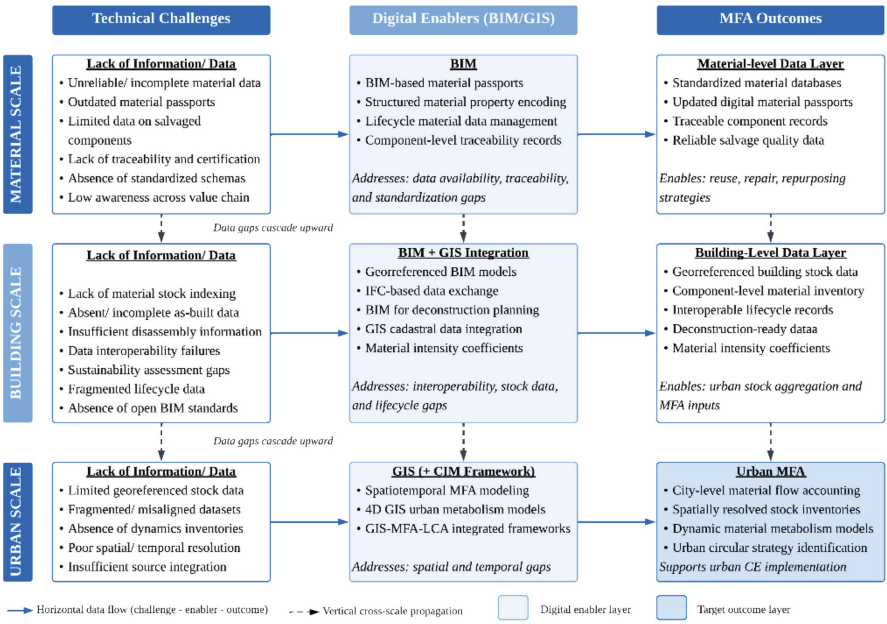


Fig. 1. Conceptual Framework: BIM and GIS as Cross-Scale Enablers for Urban Material Flow Analysis

At the material scale, BIM-embedded material passports and standardized product data libraries provide the foundational input data. At the building scale, BIM models enriched with material attributes, complemented by GIS-based spatial registration, enable characterization of the building stock. At the urban scale, spatially aggregated building stock data, processed through GIS-enabled MFA platforms, support city-level resource flow quantification and circular strategy identification.

This framework contributes to operationalizing CIM as a data infrastructure for urban circularity, emphasizing the importance of upward data flow from material characterization to urban analysis. Furthermore, the framework highlights that the resolution of urban-scale data challenges is conditional upon addressing their antecedent causes at lower scales.

6 Conclusions and Future Research Directions

This paper has discussed the cross-scale technical challenges that impact material flow analysis at the urban level, with particular focus on data and information deficiencies. Through a structured desk research approach, it has mapped correlations between challenges at the material, building, and urban scales, and identified how BIM and GIS technologies have been employed, individually and in integrated form, to address these challenges. The proposed conceptual framework offers a structured perspective on how digital technologies, when applied at lower scales, can generate upward data flows that enhance urban MFA capacity. By positioning BIM and GIS as cross-scale enablers within

a CE framework, the study underscores the need for integrated digital strategies that span from material characterization to city-level resource governance.

Several limitations should be acknowledged. First, the study is based on desk research and is therefore subject to publication bias and limited coverage of practitioner-driven or grey literature. Second, the relevance levels assigned to challenges are based on frequency of mention in the reviewed literature; they indicate prominence in research, not validated real-world priority. Third, the cross-scale correlations proposed in this paper are literature-informed analytical relationships and should not be interpreted as empirically confirmed causal links. Future research should focus on validating the relevance of challenges in real-world applications, developing and testing data pipelines that operationalize the proposed framework, including integrating material passport systems with BIM platforms and GIS-based urban stock databases. Comparative case studies across different urban contexts will be instrumental in refining the framework and assessing its transferability.

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Explainable Anomaly Detection in Thermal Insulation Material Profiles: A Multi-Feature Case Study from Greece

Konstantinos Papachatzis(✉)

Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
knpapacha@civil.auth.gr

Abstract. This study proposes an explainable anomaly detection framework for identifying irregular thermal insulation materials across multiple key features, focusing on the Greek market. The analysis utilizes a dataset of 500 products sourced from technical leaflets, Environmental Product Declarations (EPDs), and market surveys, incorporating thermophysical, technical, environmental attributes, and retail prices. Initially, k-means, Gaussian Mixture Models (GMM), and Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) were evaluated for identifying natural groupings within the dataset, yielding silhouette scores of 0.77, 0.77, and 0.79, respectively. HDBSCAN proved most effective at capturing the underlying density structure and actively isolating noise. Following HDBSCAN cluster assignment, GMM profiled the internal distributions of the pure clusters. A sensitivity analysis across three threshold scenarios (1%, 5%, and 10%) was then employed to rigorously evaluate the stability of the profiling findings. Finally, a decision-tree (DT) model extracted transparent, human-readable rules defining anomalous materials. The results highlight that thermal resistance, recommended application, price, and Global Warming Potential (GWP) critically drive anomalous behavior. From these, three actionable "if-then" rules are derived—identifying contextual niche failure, commercial discrepancy, and environmental deviation. Ultimately, by explicitly linking economic viability with lifecycle environmental impacts, this approach operates circular economy principles; it empowers stakeholders to move beyond basic material selection toward designing greener and competitive products.

Keywords: thermal insulation materials · anomaly detection · unsupervised clustering · explainable machine learning

1 Introduction

Globally, the building sector accounts for approximately 32% of energy demand and 34% of anthropogenic CO_2 emissions [1]. Furthermore, building and construction activities contribute to around 18% of emissions in the form of embodied carbon, primarily driven by the production of energy-intensive materials such as concrete and steel [1]. Beyond energy consumption and greenhouse gas emissions, the building sector is one of the most significant consumers of natural resources, generating approximately 35 billion tons of waste that ends up in landfills [2].

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Therefore, achieving complete decarbonization in the building sector requires a rigorous whole life cycle assessment [3]. Moving another step forward from the concept of "green" to the concept of "sustainable" implies considering all three pillars of sustainability [4]. In this context, factors such as cost-optimal levels, thermal and visual comfort, aesthetics, and healthiness, among others, must be considered [5–7].

In the pursuit of sustainable new and retrofitted buildings, the envelope acts as the primary interface between the indoor and ambient environment, governing the building's response to external climatic stimuli. Consequently, thermal insulation is paramount, as its thermophysical properties directly dictate key performance aspects, notably hygrothermal behavior, fire safety, and acoustics.

1.1 Objectives

This study aligns with a prominent research direction focused on developing frameworks, decision-making tools, and methodologies for optimizing both insulation manufacturing and selection. Furthermore, it builds upon the author's previous work in this domain, which proposed two supervised machine learning (ML) models to predict the retail price of insulation materials within the Greek construction market [8]. These models were trained on a dataset of 500 commercial materials, utilizing their thermophysical, technical, and environmental attributes as predictors [8].

Using the same dataset, this study initially employs unsupervised clustering techniques to identify groups of insulation materials with similar sustainability profiles. Building on these clustering results, the second objective is to derive explainable rules for unseen materials by applying anomaly detection techniques.

2 Literature Review

Supervised ML methods have been widely applied in the research field of building materials to accurately predict numerous properties [9]. However, there is a scarcity of research applying unsupervised ML, particularly clustering techniques, to building materials.

Zhao et al. [10] employed Density-Based Spatial Clustering of Applications with Noise (DBSCAN) to dynamically choose appropriate reference values for key predictors of vacuum glass insulation performance. Alternatively, Wang et al. [11] conducted Agglomerative Hierarchical Clustering on daily time-series data representing the hygrothermal transfer from outside through an exterior wall. The goal was to create clusters of daily time series with similar trends to identify general patterns with better accuracy.

Moreover, Zia ul Haq and Ricciotti [12] utilized particle clustering analysis on Scanning Electron Microscopy images of geopolymer composite brick samples to gain insights into the underlying causes of compressive strength variation. On the other hand, Alami et al. [13] used k-means clustering on a dataset of thermal properties of palm and esparto-fiber reinforced concrete samples, aiming to segregate the data into homogeneous groups with shared thermal characteristics.

Focusing on unsupervised anomaly detection within the scope of the building sector, Fan et al. [14] proposed an autoencoder-based ensemble method for detecting anomalies in building energy data. In the same vein, Fahim et al. [15] introduced a time-series-to-image model to identify anomalous energy consumption in residential buildings.

3 Materials and Methods

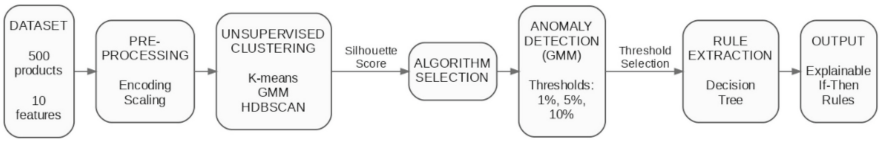


Fig. 1. Methodology flowchart.

3.1 Dataset Description and Preprocessing

This study utilizes a dataset comprising 500 commercial insulation materials sourced from the Greek construction market (Fig. 1) [8]. To comprehensively capture the materials' sustainability profiles—encompassing performance, utility, safety, environmental impact, and economic cost—ten key variables were selected: (1) recommended application, (2) thermal resistance [m^2K/W], (3) density [kg/m^3], (4) compressive strength [kPa], (5) fire resistance, (6) vapor diffusion coefficient, (7) waterproofness, (8) noise resistance, (9) cradle-to-grave (including Module D recycling benefits) GWP [$kgCO_2eq/m^2$], and (10) retail price (€/m^2).

The data were extracted from openly accessible official technical leaflets and EPDs. Concurrently, retail prices were acquired through a comprehensive market survey of construction material suppliers in Greece [8].

The initial dataset was compiled in Microsoft Excel and subsequently imported into a Python 3.14.0 environment for further data preprocessing [16]. Specifically, categorical features were encoded using One-Hot Encoding, while numerical variables were scaled to a range of 0 to 1 utilizing MinMax Scaling.

3.2 Clustering

To achieve the primary objective, three robust algorithms—k-means, GMM, and HDBSCAN—were employed to uncover the inherent natural groupings within the dataset [16]. The k-means algorithm is an iterative clustering method designed to partition a set of data points into a pre-specified number of clusters, k, by iteratively minimizing the within-cluster sum of squares [13].

Transitioning to the second algorithm, the GMM is a probabilistic clustering method that represents a dataset as a weighted sum of multiple Gaussian distributions. Each Gaussian component corresponds to a distinct cluster characterized by its own mean

and covariance matrix, thereby enabling the flexible modeling of clusters with varying shapes, sizes, and orientations [17].

Finally, HDBSCAN extends DBSCAN by constructing a density-based hierarchical structure and extracting the most persistent clusters. It calculates mutual-reachability distances to form a weighted graph [18], from which a minimum spanning tree is derived to build the cluster hierarchy. Clusters are ultimately identified based on their stability across varying density levels [19].

3.3 Anomaly Detection

Building upon the initial clustering results, a GMM was employed to meticulously profile the internal distribution of each identified cluster [16]. Unlike methods that merely calculate geometric centroids, the GMM characterizes each cluster probabilistically by estimating its mean vector (μ) and covariance matrix (Σ), thereby capturing the exact shape, spread, and orientation of the data [17].

Consequently, an anomaly score—derived from the log-likelihood—was calculated for each data point by evaluating its probability density within its assigned cluster's distribution. To rigorously assess the sensitivity of these findings, anomaly thresholds of 1%, 5%, and 10% were subsequently evaluated.

3.4 Rule Extraction

To extract explainable rules, an interpretable DT classifier—restricted to a maximum depth of 3 to prevent overfitting—was trained exclusively on the pure clustered instances, deliberately omitting HDBSCAN noise [16]. To counteract the severe class imbalance, a balanced class weight parameter is applied. By utilizing the original, unscaled material variables as inputs and the GMM-derived binary anomaly labels as targets, the DT generated transparent "if-then" rules that highlight the exact thresholds driving the anomalies.

4 Results

4.1 Clustering Interpretation

The clustering results indicate that all employed methods exhibit satisfactory performance when subjected to quantitative validation using the silhouette score. Both k-means and GMM suggest an optimal configuration of 24 clusters, yielding an identical silhouette score of 0.77. In contrast, HDBSCAN identifies 18 distinct clusters and achieves a marginally higher silhouette score of 0.79. However, it simultaneously isolates 43 materials into a "noise" cluster, classifying them as global anomalies. These global anomalies correspond to materials with limited representation within the dataset.

It is worth noting that HDBSCAN not only achieves a superior silhouette score, but it also actively isolates noise. This prevents the cluster contamination that typically occurs with the forced assignment mechanisms of k-means and GMM. Consequently, HDBSCAN was selected as the most robust and suitable clustering method for this study.

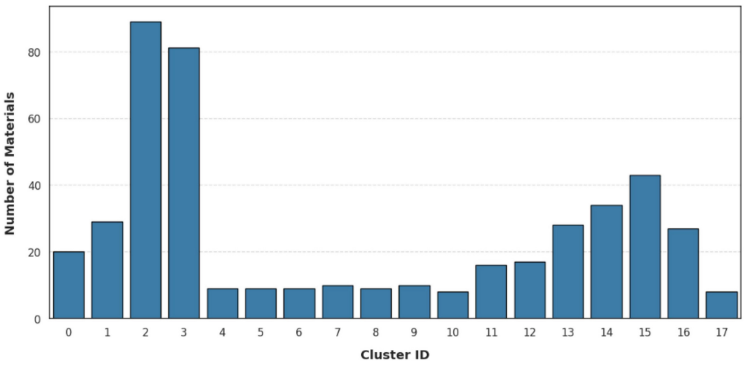


Fig. 2. Material distribution across the 18 clusters identified via HDBSCAN.

As illustrated by the GMM profiling of the HDBSCAN results (Fig. 2), the highly uneven cluster sizes underscore a heterogeneous market comprising both densely populated clusters of widely used materials and smaller clusters of niche products. Driven by the high-dimensional, density-based nature of HDBSCAN acting on one-hot encoded variables, materials within the same cluster exhibit strict uniformity in their base type, confirming they reflect true functional product families.

4.2 Sensitivity Analysis

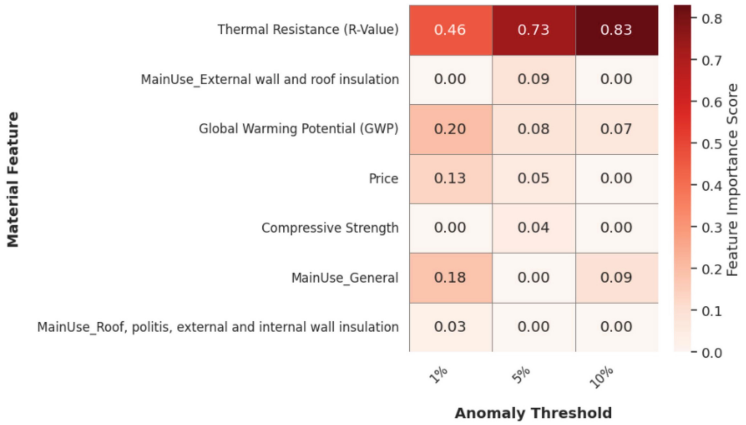


Fig. 3. Feature importance sensitivity across anomaly thresholds.

As illustrated in Fig. 3, thermal resistance emerges as the most critical feature in the profiling process across all three threshold scenarios. Importantly, GWP maintains a significant and consistent influence on the profiling results regardless of the scenario.

For the subsequent rule extraction phase, the 1% threshold scenario was selected; this stricter threshold effectively filters out vague performance variances to isolate genuine,

multidimensional market anomalies, thereby generating logical and actionable rules through the DT.

4.3 Anomaly Rules

As detailed in Table 1, the DT successfully derives three distinct anomaly rules, which are characterized as contextual niche failure, commercial discrepancy, and environmental deviation.

Table 1. Explainable rules defining contextual anomalies (1% threshold).

ID	Anomalous conditions (IF)	Physical and market interpretation
1	R-Value <= 0.93 AND Rec. appl. ≠ General AND Rec. appl. ≠ Roof / Pilotis / Wall	Contextual niche failure: Severe thermal underperformance restricted to highly unconventional or specialized application categories.
2	R-Value >0.93 AND GWP < = 41.04 AND Price <= 1.17	Commercial discrepancy: Relatively low pricing for materials exhibiting adequate thermal resistance and moderate environmental impact (potential dumping or mispricing).
3	R-Value >0.93 AND GWP > 41.04 AND GWP < = 43.70	Environmental deviation: Acceptable thermal performance compromised by an elevated, highly specific environmental footprint (GWP) relative to its peer cluster.

5 Discussion and Conclusions

The extracted explainable rules serve as valuable market-oriented decision-making tools that directly operate circular economy principles. By integrating a strict cradle-to-grave lifecycle perspective—capturing Module D recycling benefits within the GWP—alongside retail prices, the framework concurrently evaluates environmental and economic viability. Because these specific sustainability metrics significantly drive anomaly identification, the approach actively penalizes linear manufacturing profiles. Ultimately, it empowers stakeholders to move beyond basic material selection toward designing greener, competitive products that reduce environmental footprints, facilitate reuse, and maximize end-of-life recyclability.

However, several significant limitations must be acknowledged. First, the dataset is spatially and temporally constrained. Furthermore, the analysis does not account for other critical environmental and economic factors that influence material sustainability. Finally, the proposed approach is strictly data-driven; it identifies anomalies and extracts rules based solely on the patterns within the existing dataset, and thus should not be conflated with prescriptive rules designed to achieve predefined sustainability goals.

By integrating a broader range of features and exploring synergies with complementary methodologies, the proposed framework can be significantly enhanced. Furthermore, through regular data updates and the inclusion of new products via federated learning techniques, more effective and trustworthy anomaly rules can be extracted. Ultimately, these refined rules could serve as robust guidelines for the development and selection of more sustainable thermal insulation materials.

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Reshaping Heritage Documentation: A Predictive Framework for Sustainable and Resource-Circular HBIM Survey Planning

Rnin Salah[1](✉), Nóra Géczy[2], Beatrice Vîlceanu[3], and Kitti Ajtayné Károlyfi[1]

[1] Department of Structural and Geotechnical Engineering, Széchenyi István University, H-9026 Győr, Hungary
salah.rnin.riziq@hallgato.sze.hu
[2] Department of Architectural Design, Széchenyi István University, H-9026 Győr, Hungary
[3] Department of Overland Communications Ways, Foundations and Cadastral Survey, Faculty of Civil Engineering, Politehnica University of Timisoara, 300223 Timisoara, Romania

Abstract. The transition toward sustainable practices in the built environment must extend to the digital documentation of cultural heritage. Traditional Historic Building Information Modeling (HBIM) survey workflows frequently operate under reactive paradigms, identifying data gaps only during post-processing. This approach often results in redundant site visits, repeated equipment mobilization, and avoidable resource waste. This study presents a multi-criteria decision-support framework for sustainable and resource-circular HBIM survey planning. Powered by the Predictive Scan Feasibility Estimation Model (PSFEM), the framework embeds predictive feasibility assessment directly into the planning phase. Rather than treating documentation gaps as retrospective metrics, it anticipates occlusions and coverage limitations prior to field deployment, enabling proactive strategy selection between ground-based and hybrid acquisition. The framework was validated across two Hungarian chapel case studies characterized by contrasting environmental constraints. At the vegetation-constrained Sopronhorpács Chapel, predictive assessment identified ground-based limitations in advance, supporting a targeted hybrid UAV–TLS intervention that increased geometric completeness from 54% to 96% within a single consolidated acquisition phase. At the Lucsony Szent Anna Chapel, predictive distance analysis demonstrated that optimized far-range scanning achieved 100% roof coverage, compared to 74.9% under close-range conditions. The results confirm that embedding predictive intelligence into HBIM survey workflows fosters resource circularity, minimizes environmental impact, and provides an accessible foundation for sustainable digital heritage acquisition across diverse architectural typologies

Keywords: HBIM · Sustainable Survey Planning · Resource Circularity · Predictive Decision-Making · Terrestrial Laser Scanning (TLS) · UAV Photogrammetry

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1 Introduction

Sustainability in the built environment has traditionally focused on material efficiency, operational performance, and life-cycle assessment. However, sustainable practice also requires responsible management of the digital processes that support conservation and long-term stewardship of cultural heritage [1]. As Historic Building Information Modeling (HBIM) becomes a central instrument for documentation and intervention planning [2, 3], the environmental and organizational implications of survey planning itself demand closer examination. HBIM depends on accurate geometric acquisition, and terrestrial laser scanning (TLS) is widely adopted due to its precision and density. Yet heritage environments rarely offer ideal scanning conditions. Irregular geometries, height variations, vegetation, restricted access, and constrained urban settings frequently obstruct line-of-sight visibility. When completeness is verified only after acquisition, deficiencies in elevated or occluded areas often necessitate additional field visits. These reactive loops increase transportation emissions, equipment time, processing effort, and project duration, contradicting principles of minimal intervention and resource efficiency [4].

While HBIM research has focused primarily on modeling accuracy, interoperability, and data integration [5, 6], less attention has been given to the sustainability of survey planning. Circularity principles emphasize maximizing value per resource input while minimizing redundant cycles [7]. In digital heritage documentation, this implies achieving maximal geometric completeness per mobilization event.

Addressing this challenge requires reframing completeness as a predictive planning parameter rather than a retrospective quality metric [8]. Hybrid TLS–UAV strategies are often introduced only after terrestrial limitations become evident [9]. Embedding predictive feasibility assessment prior to deployment enables proportionate, risk-aware strategy selection [10].

In response, this study introduces a sustainability-oriented decision-support framework that builds upon the Predictive Scan Feasibility Estimation Model (PSFEM) established in [11] and its uncertainty-aware formulation developed in [12], embedding these within a resource-circularity architecture that translates predictive feasibility outputs into operational efficiency indicators for more responsible digital heritage acquisition.

2 Methodology and Case

2.1 A Predictive Workflow Architecture

The proposed methodology restructures conventional HBIM survey planning into a predictive and resource-aware architecture. Instead of executing acquisition first and evaluating completeness afterward, feasibility assessment is embedded as a pre-deployment decision layer. The workflow comprises four interdependent stages (Fig. 1):

1. Preliminary Assessment: Documentation objectives required detail levels, and site constraints (vegetation, access, building height, roof inclination, setbacks) are recorded.

2. Predictive Feasibility Assessment: Planned TLS positions are evaluated using PSFEM to estimate the risk-adjusted Scan Fit Index (SFIadj).
3. Strategy Selection and Execution: Risk levels determine whether TLS-only or hybrid TLS–UAV acquisition is implemented.
4. Data Integration and Verification: Datasets are registered and evaluated, minimizing the need for iterative field returns.

This architecture transforms survey planning from a linear "acquire–verify–correct" model into a circular system in which predictive evaluation precedes resource commitment. By embedding decision logic before mobilization, environmental impact is addressed at the earliest possible stage.

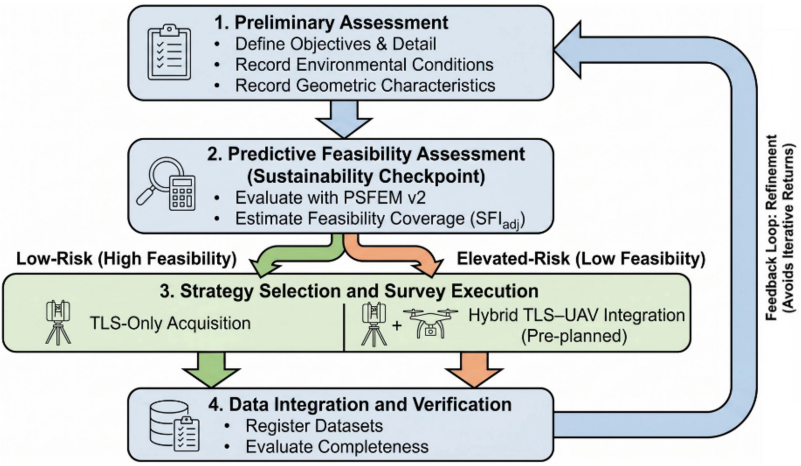


Fig. 1. Predictive Decision-Support Workflow for Sustainable and Resource-Circular HBIM.

2.2 Predictive Feasibility and Environmental Modifiers

Within the framework, PSFEM functions as a pre-deployment risk estimator, building upon the uncertainty-aware formulation developed and empirically validated in [12]. The SFIadj quantifies the expected geometric coverage achievable from a planned TLS position under prevailing site constraints. The base geometric feasibility is calculated as $SFI = \min((Rs \times \sin\theta) / Hb, 1.0)$, where Rs is the effective scanner range, θ is the vertical clearance angle, and Hb is building height. The min function caps the score at 1.0 to maintain consistency with the normalized risk-threshold scale. The environmental uncertainty modifier is then calculated as $U = 0.5(VDI) + 0.3(AF)$, where VDI is the Vegetation Density Index ($\in [0,1]$) quantifying line-of-sight obstruction from canopy cover, and AF is the Access Factor ($\in [0,1]$), where $AF = 0$ indicates unconstrained scanner placement and $AF = 1$ denotes fully restricted access. The final adjusted feasibility index is calculated as $SFIadj = SFI \times (1 - U)$. Higher VDI values reduce effective visibility, while higher AF values constrain scanner placement options. Both modifiers

are classified using a shared four-level scale (Table 1). The resulting SFIadj value is mapped to the risk thresholds in Table 2, directly informing strategy selection between TLS-only and hybrid acquisition.

Table 1. Environmental Modifier Classification Scale (applied to both VDI and AF).

Modifier Range	Interpretation
0.0–0.2	Minimal constraint
0.3–0.5	Moderate constraint
0.6–0.8	High constraint
0.9–1.0	Severe constraint

2.3 Case Evidence: Application Across Contrasting Constraint Conditions

To evaluate the practical and sustainability-related impact of the proposed framework, empirical validation was conducted across 44 TLS scan positions distributed between two Hungarian chapel case studies (Fig. 2). The selected sites represent contrasting constraint conditions: one dominated by environmental occlusion and restricted access, and the other characterized primarily by geometric sensitivity related to scanner-to-building distance.

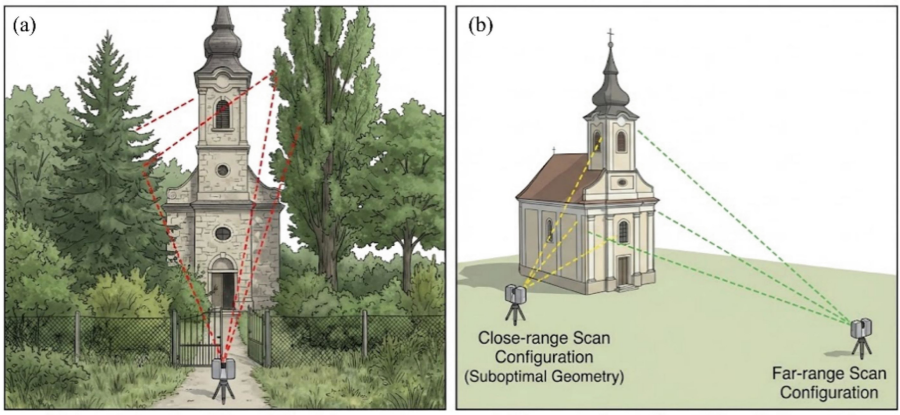


Fig. 2. Environmental and Geometric Constraints at the Case Study Sites: (a) Sopronhorpács Chapel showing vegetation obstruction and tower height and (b) Lucsony Szent Anna Chapel illustrating close- and far-range scan configurations.

This dual-case configuration enabled assessment of two distinct but complementary sustainability challenges: (1) macro-occlusion caused by environmental factors, and (2) inefficient acquisition geometry caused by suboptimal setback configuration.

Sopronhorpács Chapel: Environmental Macro-Occlusion. The Sopronhorpács Chapel features a 27 m tower partially enclosed by dense vegetation and constrained setback zones, conditions that severely restrict vertical visibility and limit effective TLS coverage. An initial TLS-only campaign comprising 28 scan positions achieved just 54% geometric completeness, leaving substantial gaps in the elevated tower and roof regions and highlighting the limitations of ground-based acquisition under environmental obstruction. Predictive feasibility assessment identified multiple positions as low-feasibility before additional mobilization occurred, thereby preventing iterative TLS-only attempts. Instead, the framework triggered a targeted hybrid TLS–UAV strategy, resulting in an integrated dataset with 96% geometric completeness, an absolute increase of 42 percentage points, achieved within a single consolidated acquisition phase. Beyond the numerical increase in coverage, the key sustainability outcome lies in the avoidance of redundant field returns and ineffective terrestrial redistribution. Environmental uncertainty was thus reframed from a reactive obstacle into a managed planning parameter embedded within the acquisition strategy.

Lucsony Szent Anna Chapel: Geometric Setback Optimization. The Lucsony Szent Anna Chapel provided a controlled setting to evaluate scanner-to-building distance as a determinant of coverage efficiency. Unlike the vegetation-constrained Sopronhorpács site, this context allowed systematic variation of setback geometry through two TLS configurations: a close-range setup comprising 10 positions at an average distance of 4.71 m, and a far-range configuration comprising 12 positions at an average distance of 14.78 m. Despite higher nominal point density at close proximity, the close-range configuration achieved only 74.9% roof coverage, as acute incidence angles restricted vertical reach and effective visibility. In contrast, far-range positions achieved complete (100%) roof coverage by improving geometric incidence conditions. Predictive feasibility assessment identified the far-range configuration as optimal prior to execution, thereby preventing inefficient close-range over-collection and eliminating the need for corrective hybrid escalation. In this case, sustainability gains were achieved not through technological substitution but through geometric optimization, demonstrating that resource efficiency can emerge from calibrated positioning rather than increased equipment deployment.

Cross-Case Synthesis: Complementary Sustainability Processes. The two cases reveal complementary sustainability pathways: at Sopronhorpács, predictive occlusion identification enabled consolidated hybrid deployment; at Lucsony, distance calibration optimized geometric incidence and avoided unnecessary data collection. In both contexts, the framework functioned as a pre-commitment filter, evaluating limitations before resource expenditure rather than correcting them afterward.

3 Results

3.1 Predictive Performance Across 44 Positions

The performance metrics reported below are based on the empirical validation dataset introduced in [12], and are re-evaluated here from the perspective of resource efficiency and sustainable survey planning. While the case studies illustrate context-specific effects,

the overall sustainability contribution of the framework is best evaluated across the complete dataset of 44 scan positions. Predictive assessment was applied prior to evaluating actual coverage outcomes, enabling direct comparison between anticipated and realized performance. Across all positions, the framework achieved an overall prediction accuracy of 88.6%, compared to 68.2% under the deterministic predecessor, an improvement of 20.4% that strengthens reliability in pre-deployment decision-making. Most critically, false-positive predictions, positions expected to achieve adequate coverage but failing in practice, were reduced from 14 to 5, corresponding to a 64.3% reduction in ineffective deployments. Each false positive represents equipment time, energy consumption, and logistical coordination expended without sufficient geometric return. Simultaneously, correctly identified infeasible positions (true negatives) increased from 9 to 15, reflecting improved anticipation of limitations and earlier identification of hybrid requirements. Together, these shifts demonstrate that sustainability gains emerge primarily from preventing waste before mobilization rather than compensating for it afterward.

3.2 Operational Decision Thresholds

The SFIadj values were translated into risk-based decision thresholds that directly informed acquisition strategy, guiding planning decisions as follows. Low-risk classifications supported TLS-only execution, moderate-risk levels enabled proportionate hybrid supplementation, and significant or high-risk conditions prevented inefficient terrestrial-only attempts. This conversion of predictive feasibility into strategy inserts sustainability within operational planning by aligning resource commitment with quantified feasibility prior to mobilization (Table 2).

Table 2. Risk-Based Operational Thresholds for Sustainable Survey Planning.

SFIadj	Risk Level	Recommended Strategy	Sustainability Effect
≥ 0.90	Low	TLS-only	Minimal equipment use
0.70–0.89	Moderate	Planned Hybrid	Controlled hybridization
0.50–0.69	Significant	Immediate Hybrid	Consolidated acquisition
< 0.50	High	UAV-dominant	Avoid ineffective TLS

3.3 Implications for Geometry-Agnostic Survey Systems

Predictive integration restructures acquisition logic beyond geometric completeness alone: it filters ineffective scan positions, consolidates acquisition phases, and prevents redundant mobilization. Because the framework operates on geometric relationships, distance, height, incidence angle, and integrates environmental uncertainty modifiers, it remains independent of specific architectural typologies, enabling transferability to towers, domes, bridges, and dense urban façades.

4 Discussion

The results indicate that sustainability gains in HBIM do not primarily stem from new hardware or increased data density, but from restructuring decision-making before deployment. By embedding predictive feasibility assessment at the planning stage, the framework shifts efficiency from post-acquisition correction to proactive design. Coverage deficiencies are no longer treated as retrospective acquisition failures but as manageable planning variables.

The sustainability contribution of this framework is evaluated through operational efficiency indicators, reduction of ineffective deployments, avoidance of repeated mobilization, and consolidation of acquisition phases, rather than through direct environmental accounting. The predictive filtering of high-risk positions reduces unnecessary equipment use, travel effort, and processing overhead, operationalizing sustainability through prevention rather than compensation [7]. Although energy use and carbon emissions were not directly quantified, the 64.3% reduction in false-positive deployments provides a measurable proxy for improved resource efficiency within HBIM acquisition workflows. At Sopronhorpács, predictive planning supported consolidated hybrid strategies to mitigate macro-occlusion; at Lucsony, distance optimization prevented inefficient over-collection [11]. These findings confirm that sustainable survey planning requires geometry-aware feasibility intelligence embedded within decision architecture [13], not technology substitution alone. Because the framework operates on spatial relationships and environmental modifiers, it remains transferable to towers, domes, bridges, and dense urban façades.

The findings demonstrate that sustainability in HBIM can be structurally embedded within workflow design, positioning predictive assessment as a governance mechanism for responsible digital resource allocation [14]. Future work should expand validation across structurally complex typologies and incorporate direct environmental performance metrics, including energy consumption and carbon emissions, to further quantify sustainability impacts.

5 Conclusions

This study demonstrates that embedding predictive intelligence within HBIM survey planning is a key enabler of sustainable and resource-circular heritage documentation, transforming reactive correction into proactive decision-making. Empirical validation across 44 scan positions confirmed improved planning reliability and reduced ineffective deployments. At Sopronhorpács, geometric completeness increased from 54% to 96% within a single consolidated phase; at Lucsony, optimized setback selection achieved 100% roof coverage without hybrid escalation. These outcomes confirm that sustainability in digital heritage documentation begins at the planning stage. By aligning acquisition strategy with quantified risk before mobilization, the framework minimizes redundant resource cycles and supports responsible digital heritage management. Future work will extend validation across additional structural typologies and incorporate direct environmental impact quantification.

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Advancing Circularity in BIM: A Comprehensive Parameter Set for Deconstruction and Reuse

Arian Loli(✉), Johannes Brozovsky, and Petra Rüther

Architecture, Materials and Structures, SINTEF Community, 7034 Trondheim, Norway
arian.loli@sintef.no

Abstract. The construction industry is increasingly adopting sustainability and circularity principles to improve resource efficiency, minimise waste, and promote reuse. Despite this progress, integrating circularity attributes of existing buildings into 3D digital models remains challenging. This study, part of the EU-funded SUM4Re project, reviewed the literature on the intersection of Building Information Modelling (BIM) and circularity to identify a comprehensive set of circularity parameters for BIM integration. Analysis of key national frameworks and circularity index tools revealed a lack of harmonised criteria and methods for assessing building circularity across countries, limiting consistency and knowledge transfer. Additionally, a review of 14 scientific articles examined BIM's role in managing circularity-related data. While research provides valuable insights, findings remain fragmented and do not cover all BIM-required data. To address this, a structured taxonomy of additional sustainability and circularity parameters for BIM integration was developed through a three-layer review. The parameters were grouped into seven categories covering core attributes at the building- or product-level. Classifying these parameters as mandatory or optional could streamline data collection and BIM integration. In addition, advanced technologies such as laser scanning and computer vision could automate parameter assessment, improving both accuracy and efficiency.

Keywords: Circularity · Building Information Modelling (BIM) · Sustainable Construction · Classification System · Deconstruction · Material Reuse

1 Introduction

1.1 Background

The construction industry is a major consumer of raw materials and a significant contributor to global waste and environmental degradation [1]. Circular economy strategies, such as reuse, recycling and recovery, are increasingly promoted to reduce these impacts and extend material lifecycles [2]. However, the transition from linear to circular practices remains challenging, due to difficulties in identifying, categorising, and assessing materials for reuse, particularly at end-of-life stages [3].

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Building Information Modelling (BIM) is a key digital enabler for managing building data throughout the lifecycle. Traditionally, BIM has focused on the design, construction, and operation phases, with limited application in demolition and end-of-life processes [4]. To bridge this gap, the concept of BIM for deconstruction has emerged, aiming to integrate circular economy principles into digital building models [5].

1.2 Research Gap and Novelty

Despite the growing body of research on the intersection of BIM and circularity, existing approaches remain fragmented and often rely on case-specific solutions. In particular, BIM-based end-of-life applications remain underdeveloped, as current implementations depend on local waste management policies, lack interoperability across platforms, and are not supported by the available BIM tools on the market [6].

The EU-funded SUM4Re project aims to establish digital material banks for the built environment by combining urban mining techniques with advanced data-collection technologies. Achieving this goal requires effective integration with BIM; however, current BIM objects are primarily optimised for new construction and lack a globally accepted framework for demolition, recovery, and reuse. These limitations reveal a key research gap: the absence of a harmonised, BIM-compatible data structure that can integrate diverse circularity data from existing buildings. To address this gap, the present study proposes a comprehensive set of circularity parameters for BIM integration, drawing on insights from the literature, existing frameworks, and digital approaches to support material recovery and improve end-of-life decision-making.

2 Methodology

This study employed a three-part, multi-layered approach to synthesise circularity-related parameters for integration into BIM: (i) a systematic review of scientific literature; (ii) an analysis of technical reports; and (iii) a review of digital record systems.

Data extraction focused on parameters, classifications, taxonomies, and data structures related to BIM from a deconstruction and circularity perspective. A consistent extraction protocol was applied across all sources to capture diverse categorisations, requirements, metadata structures, and other technical indicators. These elements were then mapped and consolidated into a unified dataset to support the development of a circularity-oriented classification and parameter set for BIM integration.

2.1 Detailed Literature Review

A systematic literature review was conducted in Scopus to identify classification approaches for BIM integration. The search combined three thematic clusters: BIM, deconstruction/disassembly, and circularity/reuse/waste, using Boolean operators and truncation to capture lexical variants. Only peer-reviewed articles, conference papers, and reviews in English were included, with no restrictions on publication years. The search, carried out in November 2024, yielded 214 documents. A two-stage screening process (initially titles and abstracts, then full texts) yielded 14 papers that discuss classification systems. The selected papers are discussed in the results section.

2.2 Technical Reports Review

The review examined EU and sector-specific national documents on deconstruction, waste audits, and circularity assessment. Unlike scientific articles, technical literature and standards are often limited or inaccessible in search databases because of language barriers or paywalls; therefore, document selection was based on expert input and prior knowledge of disassembly and reuse practices.

The analysis drew on key EU documents, including the updated Construction and Demolition Waste (CDW) Management Protocol [7] and the Waste Audit Guidelines [8]. From these documents, the study extracted procedural requirements for waste identification and categorisation to align with wider waste-management frameworks.

Technical documents such as DIN SPEC 91484 [9], and circularity index tools such as the circularity index framework of the German Sustainable Building Council (DGNB) [10] and the disassembly potential framework of the Dutch Green Building Council (DGBC) [11] were also reviewed to obtain more detailed parameters.

2.3 Digital Platforms Review

Lastly, the study examined recent developments in digital data recording systems that support material traceability, transparency, and circularity in the built environment. The focus was on the formats of Digital Product Passports (DPP) [12] and Digital Building Logbooks (DBL) [13] to retrieve lifecycle information for circular practices.

DPP was analysed to assess how it stores detailed product-level information. The DBL repository was further assessed for building-level categories, including how the logbook structure enables connections to product- and material-level datasets.

3 Results

3.1 Outcomes of Detailed Literature Review

Across the 14 reviewed scientific articles, research on BIM-enabled circularity is rapidly expanding, emphasising the need for detailed, interoperable lifecycle parameters to support reuse, recycling, and deconstruction.

Key contributions address structural reusability and salvage estimation, using quantitative models to predict end-of-life material recovery. For example, Akanbi et al. introduced a BIM-based estimator that incorporates material and connection type [14], while Mohammed et al. developed a deconstructability scoring system for steel structures based on connection reversibility and material compatibility [15].

A second group of studies focuses on material passports and component-level classification to improve transparency and traceability. Göswein et al. proposed a Circular Material Passport (CMP) that records installation data, service life, and disassembly instructions [16], while CirBIM organises material and classification data to support circularity assessment [17]. Sanchez et al. highlighted the need for detailed disassembly parameters for BIM and reuse planning [18]. In addition, Kim and Kim developed a graph-based BIM tool to evaluate deconstructability, CO_2 emissions, and reuse value, emphasising the significance of embodied energy and joint-type data [19].

The literature also discusses Design for Disassembly (DfD) and lifecycle-oriented BIM classifications. Mattaraia et al. introduced a DfD framework categorising elements by layers and disassembly potential [20], and Sanchez et al. proposed Model View Definition (MVD), an Industry Foundation Classes (IFC)-aligned model that incorporates lifecycle stages and energy requirements for disassembly [21].

Additional studies link BIM to the management of CDW and circular economy workflows. Schamne et al. [22] and Kuzminykh et al. [23] connect BIM to waste management systems and marketplaces, while Charef [24] introduces an 8D Deconstruction Information Model that includes contamination and regulatory data. Work by Gupta et al [25]., Royano et al [26]., and Jayasinghe et al [27]. highlights deficiencies in current classification systems, inconsistencies between frameworks such as Uniclass and OmniClass, and the need to incorporate logistics, safety, and secondary-market information into digital circularity workflows.

The literature shows significant progress towards a circularity-focused BIM classification, though fragmentation persists. Recurrent parameters across studies highlight an emerging need to standardise the information that BIM must record to support circular construction workflows.

3.2 Outcomes of Technical Reports Review

The review of technical literature reveals a broad yet fragmented landscape of guidance on waste audits, disassembly potential, and circularity scores. At the EU level, the CDW guidelines and protocols outline procedures for waste identification, separation, hazard detection, logistics, and quality management, thereby fostering confidence in secondary materials. National frameworks offer more detailed operational guidance. DIN SPEC 91484, through a two-stage pre-demolition audit, requires component-level data on construction year, technical documentation, material samples, pollutants, connection types, dismantlability, and reuse potential. The DGNB circularity index tool provides a quantitative method based on weighted indicators, including material origin, pollutant load, flexibility, compatibility, and recycling potential. Additionally, the DGBC framework assesses disassembly across components and building layers, considering technical, process, and financial factors, as well as concepts such as adaptability, toxicity, value development, and environmental indicators.

These developments reflected substantial progress in formalising circularity-related procedures, yet they also revealed persistent inconsistencies in scope, terminology, and classification systems. This variability highlights the need for harmonised data models, shared definitions, and interoperable classifications across jurisdictions.

3.3 Outcomes of Digital Platforms Review

The review of digital platforms revealed that DPP and DBL offer complementary systems for organising circularity data at product and building levels. DPP provides a detailed product-level profile, including information on origin, composition, manufacturing, environmental impacts, repairability, service life, and end-of-life options, supported by digital identifiers such as Quick Response (QR) codes, Radio Frequency Identification (RFID) tags, or blockchain to ensure traceability throughout the lifecycle. DBL,

meanwhile, organises building-level information, including material inventories, energy performance, renovation history, hazards, indoor-environment indicators, and circularity attributes, enabling these data to be linked across different scales.

The digital platforms demonstrated strong potential to enhance lifecycle transparency and support circularity-focused decision-making, but non-standardised data formats and limited interoperability with BIM constrain their effectiveness. These issues reduce the consistency with which DPP and DBL support workflows for reuse, recycling and material recovery in digital construction environments.

3.4 Review Synthesis

The reviews highlight significant efforts by industry, government, and research bodies, but also emphasise the fragmented, narrow, and non-standardised nature of BIM practices for demolition-related properties. Information is inconsistently organised, and terminology varies across sources, reducing coherence and efficiency. Table 1 presents a comparative summary of the three reviews conducted in this study.

Table 1. Summary of the findings from various reviews

Aspect	Detailed Literature	Technical Reports	Digital Platforms
Scope	Academic studies on circularity and BIM	Frameworks, standards, and technical guidelines	Digital tools and platforms for circularity data
Focus	Circularity parameters for disassembly and reuse	Structured methodologies and defined indicators	Data structures and implementation approaches
Type of information	Broad, diverse circularity concepts and parameters	Formalised indicators and requirements	Operational data fields and digital attributes
Strengths	Theoretical depth and range of perspectives	Structured and standardised approaches	Practical implementation and data handling
Limitations	Fragmented and heterogeneous in scope and terminology	Variability and limited alignment across frameworks	Limited interoperability and standardisation
Overall implication	Highlights the diversity of approaches	Need for aligned and harmonised frameworks	Need for BIM-compatible data structures

3.5 Circularity-Oriented Property Set

BIM provides essential data fields for detailed digital representations of buildings; however, the reviews revealed a lack of a coherent BIM-enabled structure for demolition

and circularity. To address this gap, a set of parameters encompassing key end-of-life attributes at the building- or product-level is proposed. Table 2 summarises the comprehensive set of parameters extracted from the three-layer review.

The dataset is organised into seven main categories and respective subcategories, covering various aspects of circularity in construction. Although extensive, the list is not exhaustive and can be further refined through research and practical applications.

Table 2. Dataset for integration of circularity parameters in BIM

Main category	Subcategory	Parameter
General Building Information	Building Identification	Building name / Building Address / Building Type / Year of Construction / Unique Identifier
	Maintenance, Repair, and Renovation History	Maintenance Records / Service Life of Components / State of Use and Ownership
Building Performance Indicators	Energy Performance	Operational Energy Consumption / Energy Performance Certificates (EPC) / Renewable Energy Integration
	Indoor Environmental Quality (IEQ)	Air Quality / Thermal Comfort / Lighting Conditions / Acoustic Conditions
Product and Material Information	Product and Material Identification	Primary Material Type / Product Composition / Product Name / Product Type / Product Model / Manufacturer / Origin / Manufacturing Process
Lifecycle Impact Data	Environmental and Carbon Footprint	Embodied Carbon / Other Environmental Impacts
	Water and Energy Use	Water Usage During Production / Energy Consumption During Production
Circularity and Disassembly Data	Disassembly Planning	Modularity / Product Type / Connection Type / Product Identification / Global Disassembly Model / Dependency Hierarchy / Detachability
	Disassembly Process	Disassembly and Recovery Guidelines / Accessibility / Tools and Methods / Physical Interface
	Salvageability and Circularity Data	Condition / Reuse/Recycling Opportunities / Reusability / Recyclability / Circularity Score

(*continued*)

Table 2. (*continued*)

Main category	Subcategory	Parameter
	Disassembly Performance	Disassembly Time / Disassembly Cost / Disassembly Revenue / Disassembly Energy Consumption / Disassembly Distance
Waste and Recycling Management	Waste Management and Recycling	CDW Diagnosis and Classification / Waste Destination / Waste Output Flow / Recycling and Waste Treatment Methods
	Hazardous Waste Data	Hazardous Material / Toxicity Data / Waste Scenarios for Hazardous and Toxic Waste
Certifications and Digital Integration	Regulatory Compliance	Compliance with EU and International Standards / Environmental Product Declaration (EPD) / Third-Party Certifications
	Digital Integration and Traceability	QR Code / RFID Tracking / Blockchain Storage / Documentation and Reports

4 Discussions

A major challenge is the complexity of compiling such an extensive dataset. A complete digital model of a decommissioned building would require estimates of technical, environmental, and functional properties, as well as economic, safety, and logistical data. Collecting or assessing this information is labour-intensive, increases the time and cost of demolition projects, and often relies on human judgement, introducing subjectivity. A tiered approach that distinguishes between mandatory and optional parameters would reduce complexity while maintaining the relevance of decisions.

Inconsistent terminology and classification systems hinder interoperability and reduce the comparability of circularity data across projects and regions. Current frameworks differ in their rating systems, circularity indices, and disassembly metrics, limiting the transferability of reuse practices beyond national borders. Developing unified BIM-based data structures and evaluation systems is therefore essential for systematic implementation. Advances in laser scanning, computer vision, and automated data collection can further reduce documentation effort and improve accuracy.

5 Conclusions

This study highlights the need to extend BIM models to include dedicated end-of-life properties, such as disassembly effort, material condition, contamination risks, and reuse or recycling pathways. Furthermore, incorporating building-level information, such as maintenance history, environmental and energy performance, waste classification, and hazardous material data, is essential for lifecycle transparency. Overall, the results emphasise that BIM must evolve beyond its current scope to include circularity and demolition-related information. Implementing a harmonised set of parameters can support more reliable assessment of reuse and recycling options and contribute to more circular decision-making in the built environment.

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A PSO-Based Decision Support Framework for Sustainable Tall Building Design

Gökçe Nihan Demirel(✉)

Middle East Technical University, Ankara 06800, Türkiye
nihant@metu.edu.tr

Abstract. The preliminary design phase of tall buildings plays a critical role in determining sustainable design, long-term material consumption, spatial efficiency, and environmental performance. However, early design decisions are often made with limited quantitative feedback due to the complexity of interdisciplinary performance evaluations. This paper presents a digital optimization framework for the preliminary design of tall buildings, employing Particle Swarm Optimization (PSO) integrated with parametric modelling and automated structural analysis to support sustainable design decision-making. The proposed framework links architectural design parameters—plan dimensions, core ratio, building height, and structural system—with structural performance metrics through API-based automation of finite element analyses. PSO is customized using a representative subset of design alternatives to efficiently explore a large solution space while minimizing computational effort. The optimization objectives are defined as maximizing leasable floor area and minimizing construction material demand, addressing both economic viability and resource efficiency. The methodology is applied to a design space of hypothetical tall building configurations. Results demonstrate that PSO can identify near-optimal design solutions by evaluating less than half of the total solution space, significantly reducing analysis time while preserving solution accuracy. The findings indicate that PSO-driven early-stage design exploration enables informed trade-off analysis between spatial and material efficiency. By integrating digital automation and optimization at the preliminary design stage, the framework provides a scalable foundation for sustainability assessments and future extensions toward embodied carbon evaluation.

Keywords: Sustainable Design · Particle Swarm Optimization · Preliminary Design · Tall Buildings

1 Introduction

Rapid urbanization and increasing land values have led to a growing demand for tall buildings in dense metropolitan areas. As cities expand vertically, the design of tall buildings has become a complex interdisciplinary challenge involving architectural design, structural engineering, environmental performance, and economic feasibility. Tall buildings are structurally sensitive systems where design decisions strongly influence structural efficiency, material consumption, and spatial performance.

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In the early stages of design, architects must evaluate multiple competing objectives. Maximizing leasable floor area increases the economic value of a project, whereas minimizing structural material usage supports sustainability goals and reduces environmental impact. However, these objectives are often conflicting. Increasing floor area can lead to higher structural loads and increased material consumption, while minimizing structural material may limit usable space or structural performance. Traditional design approaches often rely on sequential trial-and-error evaluations. Such approaches are inefficient when dealing with large design spaces and complex interactions between architectural and structural parameters. Consequently, designers may overlook promising alternatives or fail to fully understand the trade-offs between competing objectives.

Recent developments in computational design and optimization techniques provide new opportunities for addressing these challenges. By integrating parametric modelling, automated structural analysis, and optimization algorithms, it becomes possible to systematically explore large design spaces and identify high-performing design alternatives. This study proposes a PSO-based decision support framework for the preliminary design of tall buildings. The framework integrates parametric design variables with automated structural analyses to evaluate both spatial and material performance. The aim is not to identify a single optimal design, but to reveal high-performing design alternatives and provide insight into the relationships between design parameters and performance outcomes. Reducing the number of required structural analyses is particularly important during the preliminary design phase, where architects must evaluate multiple evolving design alternatives within limited timeframes. Rather than focusing solely on computational efficiency, the proposed framework aims to support broader design space exploration and faster comparison of competing architectural strategies.

2 Background and Related Work

Metaheuristic optimization algorithms have been widely applied in structural engineering to address complex design problems involving multiple variables and constraints. Among these algorithms, Particle Swarm Optimization (PSO) has gained attention due to its simplicity and efficiency in exploring large design spaces. Previous studies have demonstrated the effectiveness of PSO in structural optimization problems. Fourie and Groenwold (2002) applied PSO to structural size and shape optimization and reported competitive performance compared to traditional metaheuristic approaches. Perez and Behdinan (2007) and Luh and Lin (2011) further demonstrated the robustness of PSO in optimizing truss structures, highlighting its ability to efficiently search large design spaces while satisfying structural constraints. Elegbede (2005) applied PSO for structural reliability assessment under uncertainty, while Li et al. (2007) proposed a heuristic PSO approach for pin-connected structure optimization that improved convergence behavior. Multi-objective applications have also been explored, such as the VEPSO method introduced by Omkar et al. (2008), which balances competing performance objectives in composite structure design. Gholizadeh and Fattahi (2014) proposed a modified PSO algorithm for steel tall building design that improves convergence through adaptive penalty functions. More recently, PSO has been integrated with advanced analysis methods such as isogeometric analysis to optimize structural forms in building engineering applications (Tsiptsis et al., 2019).

Despite these advances, most existing studies focus primarily on optimizing structural member sizes or predefined structural configurations. Architectural parameters such as plan layout, core arrangement, and building height are often treated as fixed inputs rather than dynamic variables within the optimization process. This limitation reduces the relevance of such studies for architectural design workflows, particularly during the early design stage where decisions regarding building form and spatial organization are still evolving. To support architects during conceptual design, optimization frameworks must integrate architectural design variables and provide insights into how these variables influence structural and spatial performance. The present study addresses this gap by integrating architectural design parameters with structural analysis and PSO-based optimization within a unified computational workflow.

3 Optimization Framework

Design parameters, their variables and two objective functions are defined. The whole solution space, 810 models, is named as the target group and a subset of them, 126 models, is named as sample group. Sample group is modelled parametrically and analyses for structural performance. The results are used to customize the PSO algorithm. Then the algorithm is applied to the target group and results are compared. Figure 1 shows the overall workflow.

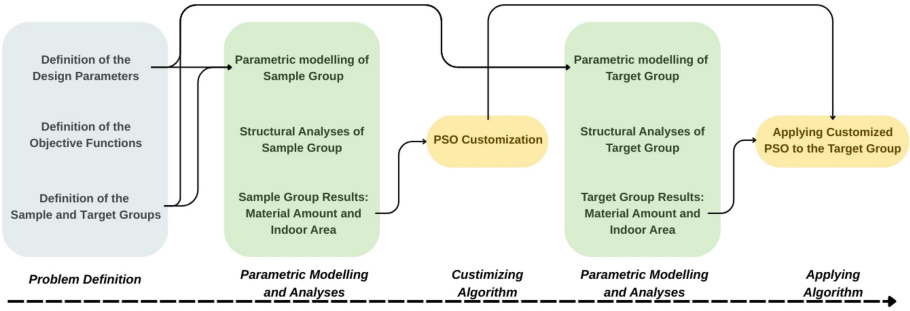


Fig. 1. The workflow of the automated optimization process

3.1 Design Parameters and Objectives

The proposed framework explores a design space defined by several architectural parameters that significantly influence spatial and structural performance: plan dimensions, core ratio, building height, and structural system. Plan dimensions vary between 30 to 50 m with 2.5-m intervals. Three different core ratios are modelled which are 18, 21 and 24%. Height of the models are 240, 300 or 360 m. Two structural systems are analysed which are outriggered frame (OF) and frame tube (FT). These inputs are defined parametrically so that multiple design alternatives can be generated automatically. Each design configuration is evaluated through structural analysis to determine its material

demand and structural feasibility. Figure 2 shows all of the parameters and corresponding variables.

Two primary objectives are defined for the optimization problem are: maximizing leasable floor area, representing spatial and economic performance and minimizing structural material consumption, representing resource efficiency and sustainability. Together, these objectives encourage solutions that provide efficient spatial use while reducing environmental impact.

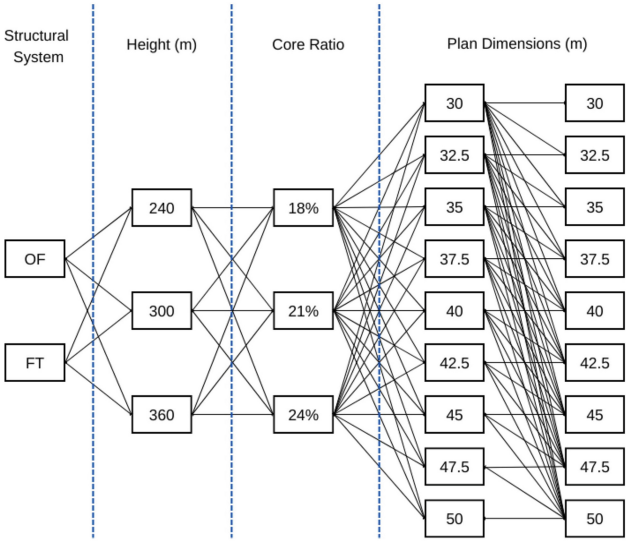


Fig. 2. Design parameters and mapping of all models

3.2 Particle Swarm Optimization Strategy

PSO is used to explore the defined design space efficiently. In the PSO framework, each particle represents a potential design solution defined by a specific combination of architectural parameters. The algorithm begins with an initial population of particles distributed across the design space. Each particle is evaluated according to the defined objective functions. During each iteration, particles update their positions based on two factors: their individual best solution encountered so far and the best solution identified by the entire swarm. This iterative process guides the swarm toward regions of the design space with better performance. The optimization process continues until convergence is achieved or no further improvement is observed. The workflow of the PSO-based optimization process is illustrated in Fig. 3.

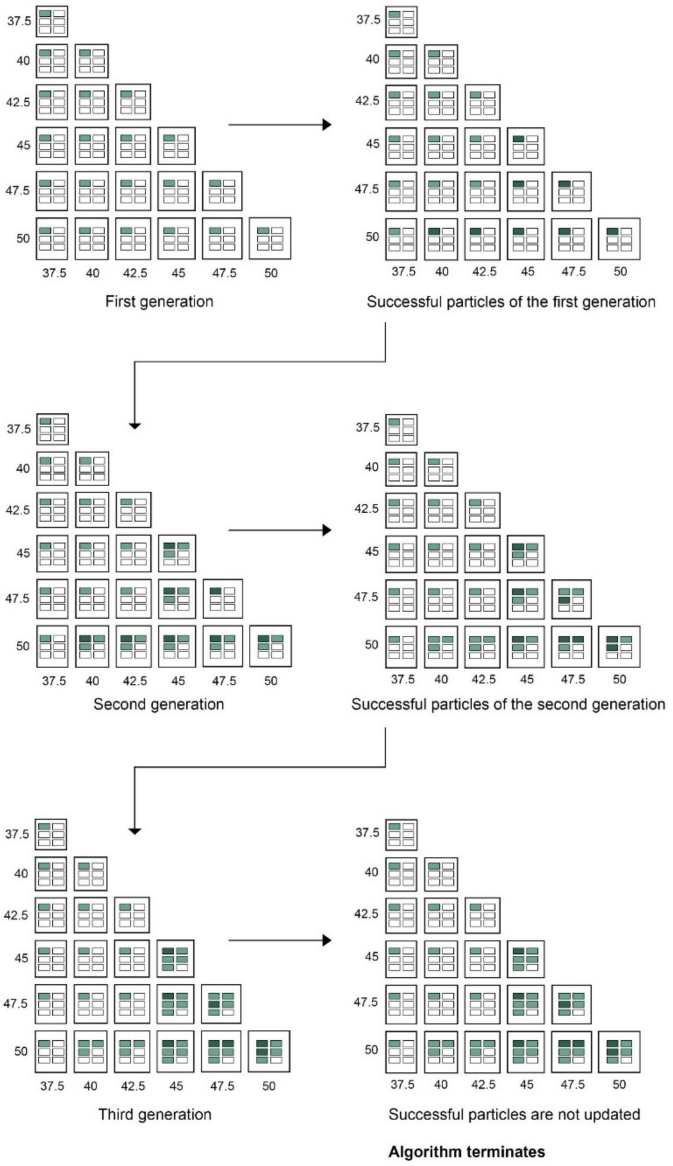


Fig. 3. The workflow of the PSO-based optimization process

4 Results

Several PSO configurations are tested by varying the number of successful particles used for generating new iterations and the number of neighbouring solutions explored. These configurations influence the exploration behaviour of the algorithm and the number of structural analyses required.

The results show that PSO can effectively identify high-performing design solutions while significantly reducing the number of required analyses. In configuration 10, the algorithm terminated before detecting the optimum solutions; therefore, this configuration was excluded from further evaluation. In the best-performing configurations, 8 and 11, the algorithm successfully detects optimal solutions by evaluating 33% of the sample group and 30% of the target group. Results of the sample and target groups are given in Table 1 and 2, respectively. The total required analyses are approximately 44% of the total solution space**.** Results also show that the performance of PSO is consistent between the sample group and the target group. Figure 4 shows the comparison of the results.

Table 1. PSO results of the sample group

Configuration	1	2	3	4	5	6	7	8	9	10	11
Size of the first generation	21	21	21	21	21	21	21	21	21	21	21
Successful cases	6	4	2	12	12	8	8	4	4	2	2
Neighbours	5	5	5	1	2	1	2	1	2	1	2
Successful iteration	1	1	2	4	2	4	2	4	2	3	4
Total number of checked models	81	61	51	81	93	61	69	41	45	29	41
Percentage	64%	48%	40%	64%	74%	48%	55%	**33%**	36%	23%	**33%**

Table 2. PSO results of the target group

Configuration	1	2	3	4	5	6	7	8	9	10	11
Size of the first generation	135	135	135	135	135	135	135	135	135	135	135
Successful cases	40	20	10	81	81	54	54	27	27	14	14
Neighbours	5	5	5	1	2	1	2	1	2	1	2
Successful iteration	2	2	3	3	2	3	2	3	2	3	3
Total number of checked models	735	435	335	459	621	351	459	243	297	191	247
Percentage	91%	54%	41%	57%	77%	43%	57%	**30%**	37%	24%	**30%**

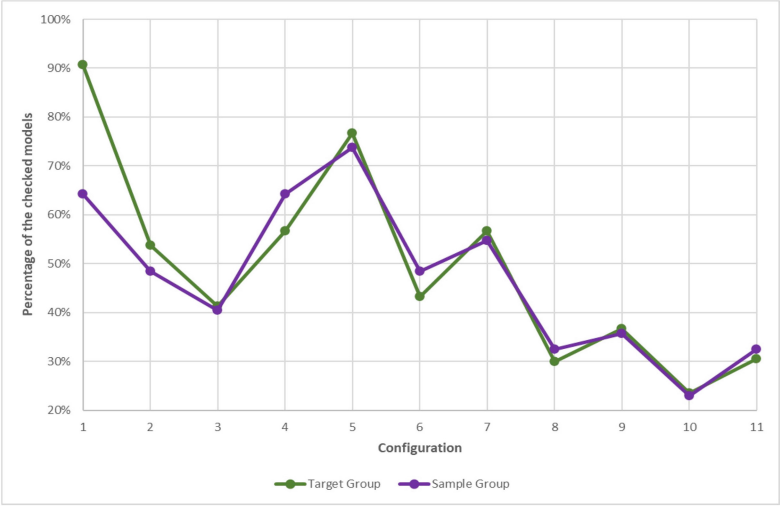


Fig. 4. Results of the sample and target group

5 Discussion

The results indicate that PSO can significantly reduce the computational effort required to identify high-performing design solutions. By exploring less than half of the solution space, the algorithm is able to locate optimal or near-optimal configurations while avoiding the need for exhaustive evaluation of all possible alternatives.

An important advantage of the proposed methodology is its integration of architectural design parameters into the optimization process. Unlike traditional structural optimization studies that focus solely on member sizing, this approach allows architects to explore how decisions regarding building form, plan layout, and core size influence structural performance and spatial efficiency. The framework also supports the exploratory nature of architectural design. Instead of identifying a single optimal configuration, the methodology detects a set of high-performing solutions that represent approximately the top 10% of the solution space. This approach provides architects with multiple viable design options and allows them to make informed design decisions based on broader performance insights. Another key advantage of the proposed framework is its scalability. Because the design parameters and optimization algorithms are defined parametrically, the framework can be extended to larger design spaces or additional performance criteria, such as embodied carbon or environmental performance metrics.

The present study has several limitations. The framework evaluates hypothetical design configurations and focuses primarily on structural material demand and spatial efficiency during the preliminary design stage. Structural analyses are based on linear elastic modelling and do not include detailed nonlinear behaviour, construction constraints, or lifecycle assessment.

6 Conclusions

This study presents a PSO-based optimization framework for supporting sustainable tall building design during the preliminary design phase. By integrating parametric modelling, automated structural analysis, and PSO, the framework enables systematic exploration of complex design spaces.

The results demonstrate that PSO can identify near-optimal solutions while evaluating less than half of the total solution space. This reduction in computational effort significantly improves the feasibility of applying performance-based design exploration during early design stages. Unlike many previous studies that focus solely on structural optimization, the proposed framework integrates architectural parameters and emphasizes the relationship between spatial efficiency and material consumption. The methodology therefore provides a practical decision-support tool for architects seeking to balance economic and environmental considerations.

Future research may extend the framework by incorporating additional sustainability indicators, such as embodied carbon and life-cycle environmental performance, as well as integrating aerodynamic performance metrics for more comprehensive tall building optimization.

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Additive Manufacturing with Earthen Materials: A Comparative Analysis of On-Site and Off-Site Fabrication Challenges

Hendrik Benz(✉) and Katharina Klemt-Albert

Institute for Construction Management, Digital Engineering and Robotics in Construction, RWTH Aachen University, Aachen, Germany
benz@icom.rwth-aachen.de

Abstract. Additive manufacturing with earthen materials is increasingly explored as a low-carbon construction approach, but remains strongly shaped by moisture sensitivity, drying behaviour, shrinkage, and environmental exposure. These characteristics make the distinction between on-site and off-site workflows especially relevant. This paper compares both fabrication settings through a focused review of literature and selected full-scale prototype references. It examines how challenge profiles change when earthen additive manufacturing shifts from direct in-situ printing toward off-site and prefabrication-oriented production. Protected off-site fabrication can reduce exposure-related instability during printing and curing, but introduces new requirements for segmentation, handling, transport, assembly, and interface coordination. By distinguishing material-related and process-related challenges, the paper clarifies that fabrication location affects not only production conditions, but also design, handling, and integration strategies. This shift is synthesized through a graphical comparison of selected material-related and process-related challenges. Off-site production therefore does not remove complexity, but redistributes it across the construction process, with implications for repairability, reuse, and circular design.

Keywords: earthen construction · additive manufacturing · on-site printing · off-site prefabrication · design for assembly

1 Introduction

Additive manufacturing with earthen materials is increasingly explored as a low- carbon and resource-conscious construction approach. Existing research has shown its potential for digital fabrication, but also its dependence on moisture sensitivity, drying behaviour, shrinkage, and changing environmental conditions. These characteristics make earthen additive manufacturing materially and operationally different from more established concrete-based construction printing.

A central question is the location of fabrication. On-site production enables direct printing in the construction setting and reduces the need to transport finished components. At the same time, fabrication remains tied to local site conditions, including machine

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setup, calibration, environmental exposure, and long-duration printing sequences. For earthen materials, this dependence can intensify uneven drying, shrinkage, cracking, and the need for temporary protection during fabrication. Off-site production offers a more controlled environment for printing and curing, but changes the construction logic once printed elements must be segmented, handled, transported, assembled, and integrated into a larger building system.

Although on-site and off-site construction printing have already been compared in the broader literature, these discussions remain shaped mainly by concrete-based systems. For earthen additive manufacturing, the comparison requires a different emphasis. Relocating fabrication does not simply improve production conditions; it redistributes challenges across the construction process. Controlled off-site production may reduce fabrication-stage vulnerabilities, but it can also introduce new dependencies related to segmentation, lifting, transport, assembly, tolerances, and long-term integration. These implications remain only partly structured for earthen systems.

This paper presents a preliminary discussion of how challenges shift between on-site and off-site workflows in earthen additive manufacturing. Based on a focused review of literature and selected full-scale prototype references, it compares both fabrication pathways through material-related and process-related dimensions. Graphical synthesis is used to highlight selected recurring challenge patterns and to show how the move toward off-site production shifts the problem field from exposure-driven fabrication constraints toward segmentation, handling, transport, assembly, and system integration.

2 Review Approach and Analytical Framing

The comparison follows a focused narrative review approach. It draws on literature from earthen additive manufacturing and from broader research on on-site and off-site construction printing to examine how fabrication location changes the challenge profile across the construction process. Sources were selected for their relevance to material behaviour, fabrication setting, and workflow-related challenges, including drying, shrinkage, cracking, environmental exposure, segmentation, transport, assembly, and interfaces.

The analytical framing distinguishes between material-related and process-related challenges. Existing earthen AM research mainly addresses material composition, printability, drying behaviour, and fabrication-stage conditions, while questions of prefabrication, movement, transport, reassembly, and interface design remain less developed, especially for earthen elements.

Selected full-scale prototypes are used as case references to ground this comparison in concrete workflow conditions. They function as contrasting examples of on-site and off-site fabrication and support the graphical discussion in Sect. 4. Table 1 links the selected challenge themes represented in Figs. 4 and 5 to the literature and case references that informed the graphical comparison.

Table 1. Selected challenge themes underlying the graphical comparison in Figs. 4 and 5, distinguishing between literature-backed themes and case-informed observations.

Challenge Theme	Dimension	Workflow	Support Type	Indicative Sources
Environmental exposure during fabrication	Material-related	On-site	Literature	[1–8]
Drying, shrinkage, and cracking risk	Material-related	On-site	Literature	[1–5, 9, 8]
Protected fabrication and curing	Material-related	Off-site	Literature	[10–13]
Segmentation for transportability	Process-related	Off-site	Literature	[10–13]
Handling, transport, and assembly interfaces	Process-related	Off-site	Literature	[2, 10–13]
Site-dependent printer setup and calibration	Process-related	On-site	Case-informed	TOVA
Temporary protection measures during fabrication	Process-related	On-site	Case-informed	TOVA
Differential drying from asymmetric exposure	Material-related	On-site	Case-informed	TOVA
Fragility during movement	Material-related	Off-site	Case-informed	ClayX / Living Prototypes

3 Case References

The presented prototypes are used as illustrative case references to ground the comparison between on-site and off-site earthen additive manufacturing. Their role is not to provide equivalent comparative datasets, but to make different workflow conditions visible through built or prototypical applications.

TOVA by the Institute for Advanced Architecture of Catalonia (IAAC) is used as the on-site reference. The project demonstrates direct printing with local earth in an in-situ construction context and shows the main logic of on-site fabrication: material remains close to its final position, transport is largely avoided, and fabrication is closely tied to site conditions and printer dimensions. At the same time, the case exposes the dependence of earthen printing on environmental exposure, site organization, machine setup, calibration, and process continuity over an extended fabrication duration (Fig. 1).

The off-site side of the comparison is represented by the contribution of IAAC to the *Living Prototypes* exhibition in Berlin and in addition early demonstrators of the *ClayX* research project [14, 15]. Both cases show earthen elements fabricated in controlled settings rather than directly in their final construction position. Their analytical

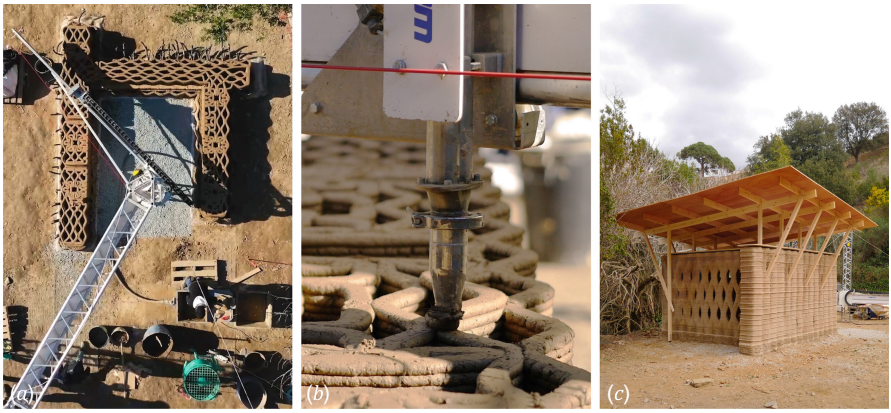


Fig. 1. TOVA by IAAC as an on-site earthen additive manufacturing case, (a) showing direct printing in context, (b) process detail, and (c) the completed prototype.

value lies in exposing the consequences of prefabrication once printed elements must be subdivided, handled, lifted, transported, assembled, and secured. Compared with the on-site case, they point less to exposure-related instability during fabrication and more to the requirements of movement, interface design, and system integration. At the same time, they indicate that prefabricated earthen additive manufacturing remains largely experimental, especially where handling, connection design, and long-term integration are concerned.

Taken together, these references provide the basis for the graphical comparison in Sect. 4, which synthesizes how material-related and process-related challenges shift between on-site and off-site earthen additive manufacturing workflows (Figs. 2 and 3).

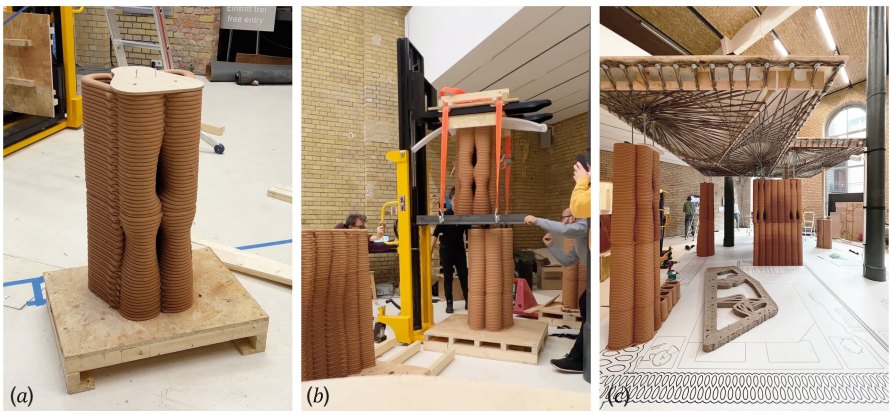


Fig. 2. Living Prototypes exhibition as an experimental prefab assembly case, showing (a) off-site prefabricated earthen components, (b) handling during installation, (c) and spatial integration in the exhibition context.

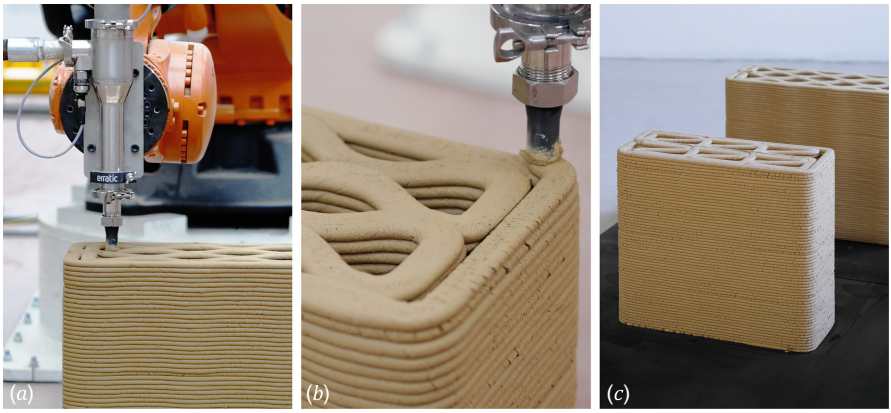


Fig. 3. ClayX as an off-site prefabrication-oriented research case, (a) showing robotic fabrication, (b) deposition detail, (c) and printed hollow test elements.

4 Comparative Discussion of Shifting Challenges

Shifting earthen additive manufacturing from on-site production to off-site prefab- rication changes the challenge profile rather than simply relocating fabrication. In on-site workflows, dominant constraints arise from environmental exposure, drying behaviour, long-duration printing, and the dependence of fabrication on local site conditions. In off-site workflows, controlled production can reduce part of this exposure-related instability, but introduces new requirements once printed elements must be segmented, moved, transported, assembled, and integrated into a larger building system. For earthen materials, this shift is especially relevant because moisture sensitivity, shrinkage, cracking risk, and early-age fragility remain active across multiple stages of the construction process. Figs. 4 and 5 synthesize this redistribution through selected material-related and process-related challenges.

4.1 On-Site Workflow: Material and Process Constraints

In the on-site workflow, the challenge field is shaped by the direct interaction between material sensitivity and site-dependent fabrication conditions. As shown in Fig. 4, material-related constraints include solar and weather exposure, differential drying, and the resulting risks of shrinkage and cracking. These effects are amplified by the fact that printing, curing, and early material stabilization take place directly in the construction environment rather than under protected production conditions. Temporary protection measures may reduce some of these effects, but they also reveal the extent to which fabrication remains dependent on changing weather and site organization.

The process dimension of on-site fabrication is equally site-bound. The printing system must be assembled locally, calibrated to the specific job site, and operated through an extended in-situ fabrication sequence. Production quality therefore depends not only on material behaviour, but on setup conditions, process continuity, and planning at the construction site itself.

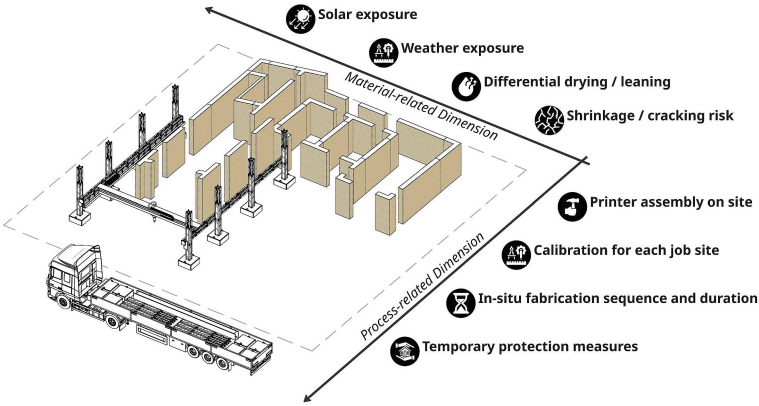


Fig. 4. Graphical synthesis of selected material-related and process-related challenges in on-site earthen additive manufacturing. The illustration highlights the dependence of in-situ fabrication on environmental exposure, drying behaviour, site-specific setup, and temporary protection measures.

4.2 Off-Site Workflow: Controlled Production and Shifted Challenges

In the off-site workflow, the challenge profile changes. Protected production settings can reduce exposure-related variability during printing and curing, making it easier to stabilize drying conditions and improve process control. Compared with the on-site case, this shifts part of the problem away from environmental uncertainty during fabrication itself. Figure 5 reflects this change through protected fabrication conditions and controlled curing. At the same time, off-site fabrication introduces a broader process-related burden. Once printed elements are no longer produced in final position, they must be segmented into transportable units, handled and lifted without damage, transported to site, and assembled with sufficient dimensional control. These steps introduce new dependencies on element sizing, movement, tolerance management, interfaces, and construction sequencing. For earthen components, these issues are intensified by fragility during movement and by the need to maintain material integrity beyond the protected production environment. The main challenge therefore shifts from stabilizing the print process under exposed site conditions toward designing printed elements as movable and assemblable components.

4.3 Shift in the Challenge Profile

Off-site earthen additive manufacturing should not be understood simply as a more controlled version of on-site printing. It shifts constraints from exposed fabrication conditions toward movement, assembly, and integration, and changes the design problem from stabilizing a continuous in-situ process to designing discrete, movable, and assemblable earthen components. This is materially significant because moisture sensitivity, dimensional instability, and early-age fragility continue beyond printing and affect handling, transport, repairability, and reuse.

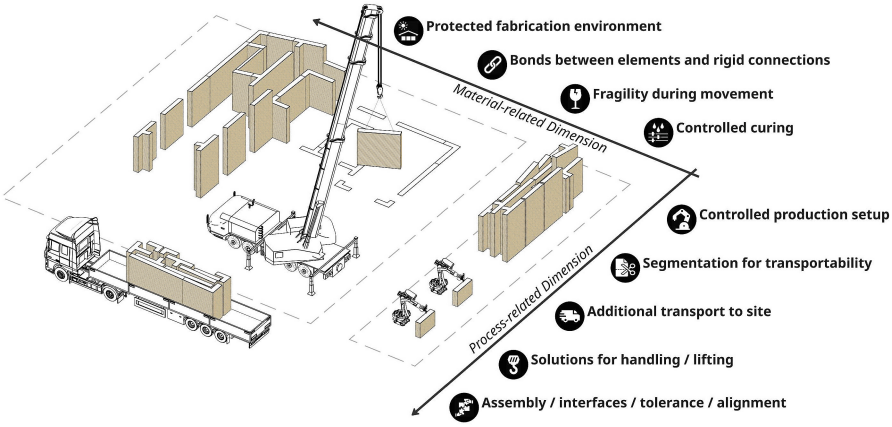


Fig. 5. Graphical synthesis of selected material-related and process-related challenges in off-site earthen additive manufacturing. Protected production conditions may reduce exposure- related instability during fabrication, but new requirements arise in segmentation, handling, transport, assembly, and interface coordination.

5 Conclusion and Future Work

The comparison between on-site and off-site earthen additive manufacturing shows that fabrication location changes the challenge profile in fundamental ways. On-site workflows are constrained primarily by environmental exposure, differential drying, shrinkage risk, site-specific setup, and long-duration in-situ production. Off-site workflows can reduce some of these fabrication-stage vulnerabilities through protected production and controlled curing, but introduce new demands related to segmentation, handling, transport, assembly, and interface coordination. Off-site earthen additive manufacturing should therefore not be understood as a simple improvement over on-site production. The main effect is a shift in where complexity occurs: from exposure-driven print-process constraints toward the movement and integration of prefabricated elements. For earthen materials, this shift is especially important because material sensitivity remains relevant beyond fabrication itself. Future work should examine segmentation, transport, reversible interfaces, repairability, and the circular potential of prefabricated earthen components.

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From Design Intent to Low-Carbon Outcome: AI as a Tool for Embodied-Carbon Reduction

Anna Thompson[1], Ola Heum Muri[1], Reyn O'Born[2], and Rolf André Bohne[1](✉)

[1] Department of Civil and Environmental Engineering, NTNU, Trondheim, Norway
rolf.bohne@ntnu.no

[2] Department of Engineering Sciences, University of Agder, Grimstad, Norway

Abstract. The construction sector is responsible for approximately 37% of global energy-related CO_2 emissions, with up to 80% of a building's environmental impact being determined during the concept and schematic design phases. The present study investigates how artificial intelligence (AI) may be operationalised as a decision-making aid for embodied-carbon reduction in early-stage building design, through a mixed-methods approach comprising a systematic literature review, 18 semi-structured interviews with architects, engineers, and real-estate stakeholders, and a comparative analysis of five commercial AI platforms applied to a real case building. Interview findings indicate that the early integration of sustainability yields performance gains, whilst AI tools are constrained by data-quality, transparency, and workflow compatibility issues. Tool analysis produced emission estimates in the range 239–509 kg CO_2e/m^2 against a professional reference of 214 kg CO_2e/m^2, with timber structures consistently yielding the lowest embodied carbon. Rule-based tools demonstrated lower deviation from the reference than data-driven platforms. In order to accelerate AI adoption, transparent data sources, BIM-compatible integration, and revised business models are recommended.

Keywords: Artificial Intelligence (AI) · Embodied Carbon · Early-Stage Building Design · Decision-Support Systems · Building Information Modeling (BIM)

1 Introduction

The construction sector is responsible for 37% of global energy-related CO_2 emissions [1]. Up to 80% of a building's embodied-carbon impact is determined during the concept and schematic design phase [2]. This is when the decisions on structural system, cladding, and geometry decisions are still open. As electricity grids decarbonise, embodied carbon is projected to become the dominant driver of greenhouse-gas-emission from buildings [3]. Traditional LCA requires detailed material quantities unavailable at this stage [4], creating a demand for rapid AI-assisted estimation tools. However, the accuracy, sensitivity behaviour, and practical usability of such tools remain insufficiently documented. The present paper addresses: How can AI be operationalised as a decision-making aid for reducing embodied carbon in early-stage building design?

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2 Background

2.1 Embodied Carbon and Early-Stage LCA

LCA, as standardised in ISO 14040/14044 and EN 15978, provides the framework for quantifying building environmental impacts across lifecycle modules A1–C4. Embodied carbon (primarily A1–A3) is governed by structural and envelope design decisions. Early-stage LCA faces a fundamental data paradox in that the phase with the highest decision leverage has the least available data. Parametric methods address this by predicting emissions from building-level descriptors, such as gross floor area, structural typology, and location, calibrated on post-design datasets [5]. Tool comparison studies have consistently revealed large inter-tool variation [6], raising questions about benchmark reliability.

2.2 AI in Sustainable Building Design and as a Decision-Support Tool

AI encompasses machine learning, neural networks, and large language models, with growing applications in the built environment [7, 8]. In carbon estimation, two model types are prevalent: rule-based tools, which generate parametric material takeoffs and apply EPD emission factors, and data-driven tools, which apply regression or ML models trained on post-design LCA datasets. From a decision-support perspective, AI carbon tools are of value when they produce outputs rapidly enough to influence a design iteration, communicate uncertainty sufficiently, and integrate with established BIM workflows [9, 10, 11]. Despite this potential, our 2024 survey of Norwegian AEC professionals identified lack of competence (80–87% of respondents), data quality, and cost as the dominant barriers to adoption.

3 Methodology

3.1 Systematic Literature Review

Searches were conducted in Web of Science, Scopus, and NTNU library collections using Boolean combinations of four concept clusters: “embodied carbon” OR “embodied GHG”; “artificial intelligence” OR “machine learning”; “early-stage design” OR “concept design”; “LCA” OR “life cycle assessment”. Inclusion criteria following PRISMA guidelines (peer-reviewed, 2015–2025, English, buildings focus) yielded 47 sources.

3.2 Interview Study

Purposive sampling was applied across three stakeholder groups: architects and design engineers (n = 9), real-estate developers (n = 5), and AI/software specialists (n = 4). Data saturation was reached at 18 interviews (45–60 min each, conducted digitally, audio-recorded with consent). Transcripts were analysed through inductive thematic coding comprising open coding, sub-theme grouping, abstraction to main themes, and cross-case validation. Participants are identified as RES 1–RES 18 to preserve anonymity.

3.3 Comparative Tool Analysis

Five commercially available platforms were selected on the basis of market presence, support for early-stage inputs, and relevance to the Norwegian AEC context: Autodesk Forma, Carbon Designer 3D (One Click LCA), C.Scale (Thornton Tomasetti), Preoptima CONCEPT, and Reduzer Automodell. Each tool was applied to the case building (Sect. 4) by the same operator using standardised inputs. Sensitivity analyses varied one parameter at a time: structural system (cast concrete, steel, mass timber, low-carbon concrete), cladding (brick, timber, glass fibre, steel panels), window-to-wall ratio (WWR: 20–40%), and floor count (6–10). Usability was assessed with the System Usability Scale (SUS; 0–100) immediately after each modelling session. An aggregate performance score (1–5 per criterion, max 15) was calculated from emission accuracy, SUS score, and modelling time.

4 Case Building

Campus Hotel Grimstad is a proposed eight-storey hotel and conference facility (7,680 m^2 GFA; developer: J.B. Ugland; architect: ENO Arkitekter) located in Grimstad, Norway. A detailed professional LCA by Sweco (NS 3720/TEK17, modules A1–A5) established a reference value of 214 kg CO_2e/m^2, which served as the benchmark for all tool comparisons. The baseline configuration comprised a cast-in-place concrete frame, brick/masonry cladding, 30% WWR, and no basement (Fig. 1).



Fig. 1. Campus Hotel Grimstad: aerial view (left) and architectural rendering (right).

5 Results

5.1 Interview Findings

Four themes emerged from thematic analysis. (i) Sustainability integration: respondents emphasised that sustainability must be incorporated from project inception, with a growing trend towards embodied carbon, material reuse, and developed. (ii) Current AI use:

tools are primarily applied to volume studies, daylighting simulation, and rapid visualization; some firms have developed in house language models to democratize access to sustainability knowledge. (iii) Challenges and barriers: low trust in automated estimates, poor workflow integration, outdated IT infrastructure, and opaque data sources were most frequently cited. As stated by RES 5: "Architectural processes cannot be replaced, but they can be optimised with respect to the environment." (iv) Future outlook: AI was expected to grow in importance for repetitive tasks, whilst the desire for a single integrated LCA-cost-BIM tool was frequently expressed but acknowledged as still distant.

5.2 Estimated Emission Levels

All five tools overestimated the reference value of 214 kg CO_2e/m^2 (Table 1; Fig. 2). Deviation ranged from +12% (Carbon Designer 3D) to +138% (Preoptima CONCEPT). It was observed that rule-based tools (Carbon Designer 3D, Reduzer Automodell) showed systematically lower deviations than data-driven platforms (Autodesk Forma, C.Scale, Preoptima CONCEPT).

Table 1. Estimated embodied carbon per tool and deviation from the 214 kg CO_2e/m^2 reference.

Tool	Model type	Estimate (kg CO_2e/m^2)	Deviation (%)
Autodesk Forma	Data-driven	347	+62
Carbon Designer 3D	Rule-based	239	+12
C.Scale	Data-driven	327	+53
Preoptima CONCEPT	Data-driven	509	+138
Reduzer Automodell	Rule-based	277	+29

5.3 Sensitivity Analysis

Tables 2a and 2b present the sensitivity of estimated emissions to changes in structural system and cladding. WWR and floor-count results are described in the text.

Mass timber was the most carbon-efficient structural option across all five tools; steel produced the highest values in four of five. Structural system had the greatest influence on emissions, with the spread widest in Preoptima CONCEPT (342–600 kg CO_2e/m^2) and narrowest in Carbon Designer 3D (182–293 kg CO_2e/m^2). Cladding type had a smaller effect; WWR showed minimal tool responsiveness. Floor count produced diverging trends across tools. Figure 3 presents the combined sensitivity results.

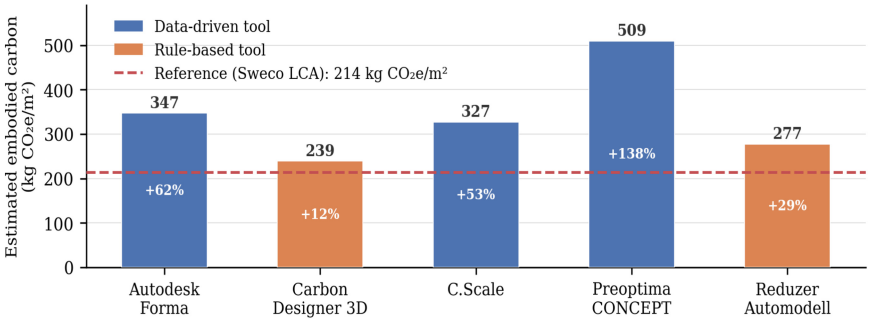


Fig. 2. Estimated embodied carbon (kg CO_2e/m^2) from five AI tools vs. reference value

Table 2a. Structural system sensitivity (kg CO_2e/m^2).

Tool	Concrete	Steel	Mass timber	Low-C concrete
Autodesk Forma	347	472	226	283
Carbon Designer 3D	239	293	182	n/a
C.Scale	327	284	219	n/a
Preoptima CONCEPT	509	600	342	349
Reduzer Automodell	277	314	241	294

Table 2b. Cladding sensitivity (kg CO_2e/m^2).

Tool	Brick/masonry	Timber	Glass fibre	Steel panel
Autodesk Forma	365	347	389	330
Carbon Designer 3D	313	239	287	304
C.Scale	251	382	241	242
Preoptima CONCEPT	482	509	496	492
Reduzer Automodell	246	277	n/a	304

Table 3 presents the lowest-emission configuration identified by each tool. All tools concur on mass timber as the optimal structural system, whilst optimal cladding, WWR, and floor count diverge substantially.

5.4 Usability and Overall Performance

SUS scores ranged from 52.5 (Reduzer Automodell) to 95.0 (Autodesk Forma and

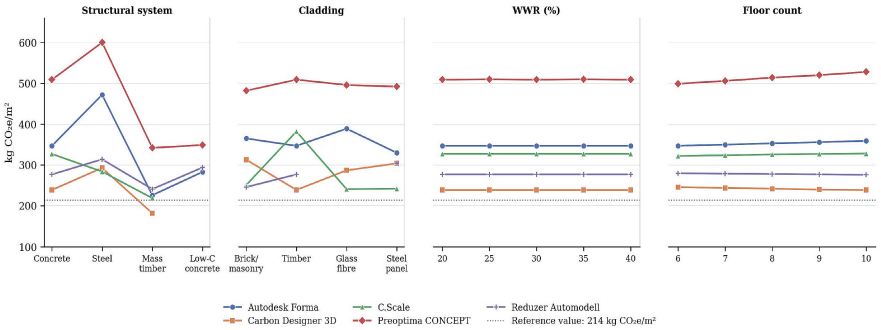


Fig. 3. Combined sensitivity line chart: CO_2e/m^2 per tool across all parameter variations (structural system, cladding, WWR, floors)

Table 3. Lowest-emission design configuration per tool.

Tool	Structure	Cladding	WWR	Floors	kg CO_2e/m^2
Autodesk Forma	Mass timber	Timber	25%	6	231
Carbon Designer 3D	Mass timber	Timber	30%	10	218
C.Scale	Low-C concrete	Low-C panel	35%	6–8	322
Preoptima CONCEPT	Mass timber	Masonry	40%	6	323
Reduzer Automodell	Mass timber	Timber	30%	8	160

Carbon Designer 3D). Modelling time ranged from 60 min (Autodesk Forma) to 210 min (Reduzer Automodell). On the aggregate performance scorecard (Table 4; Fig. 4), Autodesk Forma and Carbon Designer 3D tied at 12/15. Reduzer Automodell scored lowest (6/15), despite producing the second-smallest emission deviation, owing to poor usability and long modelling time.

Table 4. Aggregate performance scores (1 = worst, 5 = best per criterion; max = 15).

Criterion	A. Forma	C. Designer 3D	C. Scale	Preoptima	Reduzer
Emission accuracy	2	5	3	1	4
SUS score	5	5	2	3	1
Modelling time	5	2	3	4	1
Total	12	12	8	8	6

6 Discussion

6.1 Tool Accuracy and the Rule-Based vs. Data-Driven Divide

The 2.4-fold spread between the lowest (239 kg CO_2e/m^2) and highest (509 kg CO_2e/m^2) estimates raises concerns regarding single-tool reliance. In practice, outputs should be treated as relative indicators; deviations within ±30% can guide design, whilst larger divergences call for multi-tool triangulation.

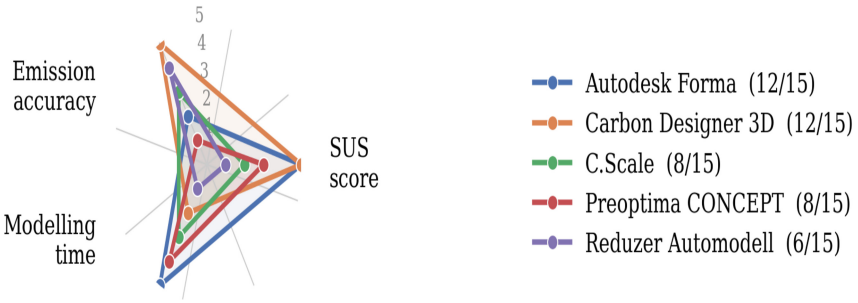


Fig. 4. Radar chart: aggregate performance scores for the five AI tools.

Systematic overestimation by all platforms may reflect broader system boundaries or conservative default assumptions. The superior accuracy of rule-based tools is consistent with comparable studies [6]: explicit parametric models render assumptions auditable, whereas data-driven tools embed assumptions within training data. The inconsistency of sensitivity responses across tools—most notably opposing floor-count trends—aligns with the low trust reported by interview participants.

6.2 Barriers, Recommendations, and Limitations

AI-based embodied-carbon tools remain at an early stage of maturity; the principal barriers are structural rather than user-related. Three clusters of recommendations are identified. For the industry: invest in capacity building, data sharing, and pilot projects linking AI outputs to actual design decisions. For tool developers: prioritise transparency of EPD sources and calculation pathways, BIM interoperability, and user control over parameters. For policy and business models: adopt project-based licensing and position AI as a decision-support layer rather than a replacement for professional judgement. Moreover, AI tools can support circular design strategies at concept stage, including low-impact material selection and design for adaptability. The study has several limitations: the tool analysis was based on a single building typology and location; the reference value covers A1–A5 under NS 3720/TEK17, whilst some tools may include additional modules, which may partly explain the systematic overestimation; and interview findings reflect the Norwegian AEC context. The reported deviations should therefore be treated as context-specific rather than universal benchmarks. Future work should replicate across typologies, normalise system boundaries, and assess inter-user variability.

7 Conclusions

Five conclusions emerge: (1) All five tools overestimated the 214 kg CO_2e/m^2 reference by $+12\% - +138\%$; rule-based platforms were more accurate than data-driven ones. (2) Mass timber was the most carbon-efficient structural system; cladding, WWR, and floor count diverged substantially. (3) AI tools add value in early-stage design, yet trust remains low due to transparency deficits and workflow incompatibility. (4) Autodesk Forma and Carbon Designer 3D performed best on the combined performance scorecard. (5) Systemic change is required: industry capacity building, transparent and interoperable tool development, and new business models that lower entry barriers. (6) Practitioners should triangulate across tools; deviations within $\pm 30\%$ can guide design, whilst larger divergences warrant professional verification.

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AI Use Declaration AI tools (Claude, Anthropic) assisted in drafting this paper. The authors reviewed and edited the full manuscript and take responsibility for its content.

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Greening the Built Environment: Traditional and AI Design Tools to Promote Circularity, Nature, and Enhance Energy Efficiency in the Refurbishment of Sassari's Municipal Swimming Pools

Antonello Monsù Scolaro(✉), Laura Ara, Roberto Mura, Alessandro Rozzo, and Silvia Pulina

Department of Architecture, Design and Urban Planning, University of Sassari, Sardinia 07100, Italy
amscolaro@uniss.it

Abstract. The adaptive reuse of the built environment presents an opportunity to reduce the exploitation of primary resources and to improve the energy efficiency of the building stock constructed over the past thirty years worldwide, in line with the European framework. This paper focuses on the refurbishment of Sassari's municipal swimming pool, beginning with a comprehensive analysis of the existing building in terms of structural, physical, and technological requirements, followed by a participatory identification of new requirements and needs. An integrated methodological approach was applied to enhance the building's environmental, social, and economic efficiency by valorizing existing materials, reducing waste, and improving technological performance; the refurbishment intervention relies entirely on dry construction solutions. The design process also incorporates principles of biophilic design to strengthen the interaction between users and nature, promoting psychological and physiological wellbeing. This approach is implemented through strategies that enhance natural daylight, visual connections with outdoor elements, and the integration of natural environmental features within the built space. In addition, thanks to the AI-powered design tools, it is shown how big data can be managed to inform design decisions that are effective from both environmental and technological performance perspectives, with particular attention to indoor air quality and user wellbeing.

Through detailed drawings, the findings present a comparative scheme of design alternatives, enabling the designer to make informed choices regarding the associated environmental impacts.

Keywords: Design for adaptability · Circularity · Biophilic Design · AI powered design tools; Bioclimatic design

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1 Circularity, Nature, and Energy Efficiency in the Refurbishment of the Built Environment

Since at least 40% of buildings in developed economies were constructed before 1980, retrofitting is challenging. In 2020, buildings represented 42% of the European Union's final energy consumption and were responsible for approximately 35% of its energy-related greenhouse gas emissions. These resulted from the direct burning of fossil fuels and energy consumption in the form of electricity, heating and cooling [1]. The EU has set a target to reduce greenhouse gas emissions by 20% by 2020 compared to 1990 levels and by more than 55% by 2030. In 2020, the European Commission launched the Renovation Wave strategy as part of the European Green Deal to promote energy-efficient renovations in the EU. Renovating existing buildings to achieve zero carbon emissions by 2030 and 2050 is crucial for meeting decarbonization goals. To achieve zero-carbon readiness in 20% of these buildings by 2030, an annual deep renovation rate exceeding 2% is required [2]. Meanwhile, the New European Bauhaus has proposed an integrated vision of sustainability, beauty, and community, requiring that every new construction or renovation project consider people's needs. A substantial body of medical and environmental research has shown that contact with natural environments provides significant physiological benefits for humans, and this need became particularly evident during the COVID-19 lockdowns [3]. Consequently, restoring meaningful connections between people and nature has become an important challenge for contemporary urban architecture [4]. In this context, by integrating natural elements and processes into the built environment, biophilic design can contribute to more sustainable architectural practices and improved resource management [5], generating multiple co-benefits, including enhanced human health and well-being, and support for climate change mitigation and adaptation. Hence, the refurbishment of existing buildings combined with biophilic design is an opportunity to create built environments that promote positive physical and psychological responses by reintroducing meaningful experiences of nature into everyday urban life.

2 The Lu Fangazzu Municipal Swimming Pool in Sassari

The swimming pools in Sassari are key landmarks in Sardinia's aquatic sports history. Designed in the mid-1970s, they feature indoor training and diving pools, alongside an outdoor Olympic-sized pool for summer competitions. The pools were inaugurated on 7 January 1981. The swimming center addressed local demand for sports infrastructure and a regional need for structured aquatic education for youth. In the 1990s and early 2000s, the complex expanded and adapted to meet the growing user demand and diverse program requirements. Rehabilitation pools, fitness area, and wellness facilities were added to the original design, enhancing community services. However, the lack of a comprehensive redesign led to spatial fragmentation and functional inefficiency over time (see Fig. 1).

The complex was built using outdated construction methods that today are no longer effective in structural terms and technological performances. The structure features a load-bearing steel frame on a reinforced concrete foundation. The exterior consists of

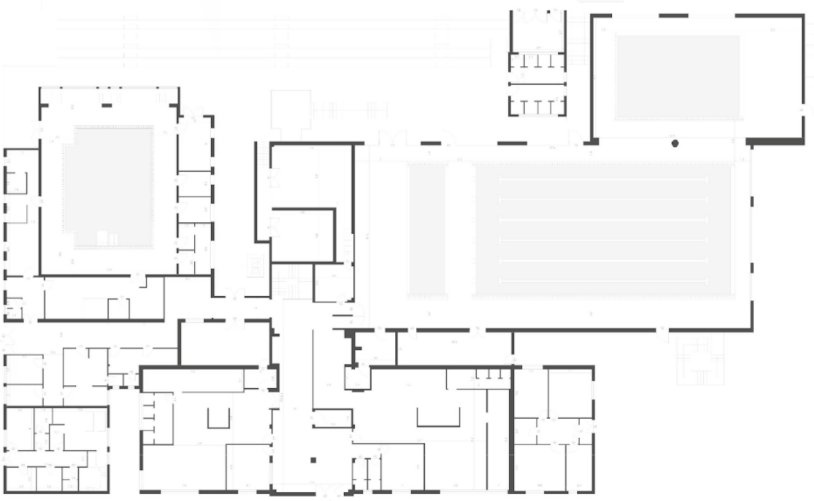


Fig. 1. The actual plan with the evident fragmented spaces (source: Ara L., Mura R., 2025).

concrete blocks rising to 1.5 m, topped with brick that includes an inner rock wool insulation layer and an internal brick finish. Roofs are categorized into two types: 1) the common space roof, made of galvanized corrugated steel sheets on steel beams with concrete, waterproofing, and gravel layers; 2) the swimming pool roofs, built with metal trusses, secondary beams, sheet metal insulation panels, and polyurethane foam. Current transmittance values: perimeter walls 0.45 W/m^{2}K, ground slab 2.61 W/m^{2}K, ceiling 0.44–0.48 W/m^{2}K, and windows 1.65 W/m^{2}K.

Over the years, the incremental additions made for immediate operational needs have led to a fragmented floor plan, characterized by a disorganized arrangement of spaces and poor wayfinding. The outdoor area, featuring a seasonal open-air swimming pool, lacks a defined year-round function (see Fig. 2). The design strategy addresses the needs of managers and users while promoting energy efficiency, material circularity, and environmental integration.



Fig. 2. The external area and the west façade (source: Ara L., Mura R., 2025).

3 An Integrated Methodological Approach to Greening and Refurbishing the Built Environment

The design approach adopted is substantially rooted in the threefold integrated vision of the New European Bauhaus (NEB): sustainable, beautiful and together. The goal is to promote sustainable development in environmental, economic, and social aspects. The refurbishment strategy is based on three key principles: circularity, biophilia, and energy efficiency. Circularity focuses on design choices that enhance the performance of structural and material components to minimize waste, reduce raw material consumption, and maximize the reuse of building materials [6]. Biophilic design reshapes the interaction between indoor users and the outdoors [3]. Energy efficiency improves the building's envelope, leverages bioclimatic benefits, and utilises technological solutions for heating and cooling, also harnessing latent thermal energy when possible [7].

The operative approach informed decision-making at all intervention scales, from spatial reconfiguration and programmatic redistribution to envelope optimization and landscape design. The refurbishment involved a systematic analysis of the physical deterioration and functional weaknesses of the existing building systems and materials, to enhance their residual performance in terms of environmental sustainability. The design was framed through a biophilic lens, prioritizing the wellbeing of workers, users, and visitors [8]. Operatively, among the 14 recognized biophilic design patterns indicated by [9], the following were implemented in the project: 1) Nature in the space (visual connection with nature, dynamic and diffuse light, connection with natural systems); 2) Natural analogues (biomorphic forms and patterns, complexity and order).

The alternatives were evaluated using AI software to improve energy efficiency, incorporate biophilic design elements like natural light and comfort, and minimize environmental impact by preserving existing materials.

3.1 Spatial Reconfiguration

The refurbishment design intervention was developed in full compliance with the Technical Standards issued by the Italian National Olympic Committee in 2005. These standards impose specific dimensional, functional, and safety requirements that directly influence spatial organization and technical design solutions.

The design process began by fixing "spatial anchors", namely the three pools (indoor rehabilitation and 25-m training, outdoor Olympic), within whose framework all other interventions were structured. The external perimeter of the complex remained unchanged, focusing modifications solely on the interior layout. Key interventions improved spatial permeability, with two main circulation axes: an east–west axis from the main entrance to the former diving pool and a north–south axis through the rehabilitation pool entrance. The plan was simplified by removing non-load-bearing partitions, resulting in a clearer spatial arrangement while preserving the original structural grid and load-bearing system (Fig. 3).

3.2 The Envelope and the Biophilic Design Contribution

To optimize the building envelope for aesthetics and performance while maximizing passive solar gain, the existing structural framework will be largely retained. A façade

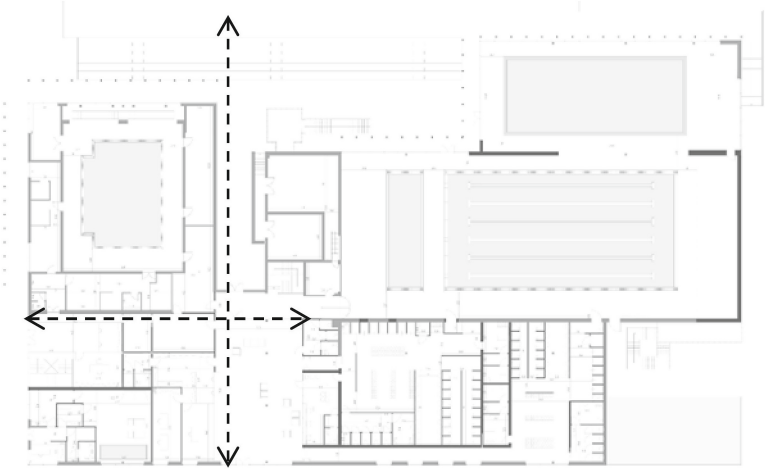


Fig. 3. The new plan with the two axes emerged (source: Ara L., Mura R., 2025).

shading system made from thin sheet metal was designed with the aim of not compromise visual connection with the surrounding landscape and based on solar radiation analysis specific to the complex's location. This established the summer and winter zenith and relative azimuth angles (see Fig. 4). The external screening geometry was verified, and the sheet metal grid was separated from the glass façade to reduce direct solar radiation in summer while allowing it in winter, optimizing natural light and occupant comfort. The building envelope features a ventilated façade with a 5 cm air gap, clad in sandwich panels made of steel sheets and polyurethane foam. The panels provide thermal transmittance values of $U = 0.536$ W/m^{2}K and $U = 0.55$ W/m^{2}K. A steel support frame, anchored to the existing wall, holds both the insulation panels and a glass façade that lets light into the swimming pools. This façade connects to the roof frame, stabilizing the entire steel structure. The envelope is completed with a new double-glazed system featuring low-emissivity glass. This system has a thermal transmittance value of $Ug = 1.1$ W/m^{2}K, representing a significant improvement on the $Ug = 5.7$ W/m^{2}K value typically achieved with single glazing (see Fig. 4).

The shading system employs a dual biomimetic design [10] with an overall wave form to evoke water and the primary function of the site, and with a pattern inspired by the structure of water molecule. The atomic mass proportions of oxygen and hydrogen are represented by two circles, with the oxygen circle being fifteen times larger and arranged according to the 104.45° bond angle. This creates an inverted 'V' shape motif that is perforated into the metal cladding, generating various openings to achieve the desired solar shading.

The vegetation strategy enabled the establishment of a multi-layered green frontage composed of arboreal, shrub, and herbaceous strata. Species were selected to ensure ecological coherence with the local context. The arboreal component consisted of both evergreen and deciduous trees to enhance users' perception of nature within the space throughout seasonal variations in foliage color and leaf fall. Tree species were specifically employed to re-establish a natural barrier along the southern boundary to protect from

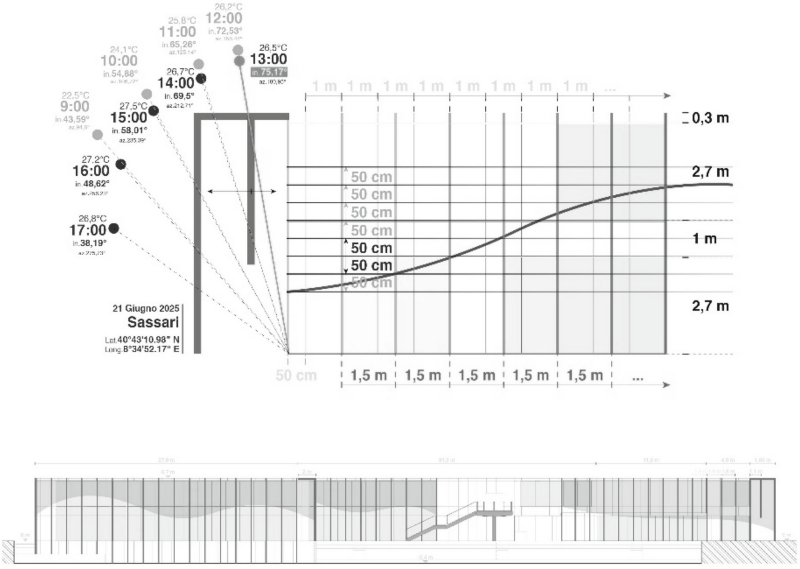


Fig. 4. Solar radiation and biomimetic western façade screening (source: Ara L., Mura R., 2025).

prevailing winds and summer solar exposure for both the outdoor pool and the west-facing façade.

3.3 The AI Design Support Decision

Afterwards, the design choices were optimized using a series of analytical tools from the American open digital platform, Cove.Tool. The EnergyPlus Weather (EPW) file enabled climate analysis of the intervention area, offering data on temperature, humidity, solar radiation, and wind. Using the psychrometric graph from the Givoni method, optimal bioclimatic strategies for the local climate were identified.

The architectural elements were assessed regarding building layers and materials, exploring alternative solutions for energy performance (thermal transmittance, U value), carbon emissions ($kgCO_2/m^2$), and renovation costs per square meter. The current situation was compared with two design scenarios: one based on traditional post-design choices aligned with regulatory limits, and another optimized for better energy performance and reduced environmental impact. Further simulations analyzed factors such as solar radiation, shading, indoor visual quality, ventilation efficiency, and air quality. Parameters were calculated based on occupancy, hours, and seasonal changes, helping to create a more realistic scenario for building energy consumption.

The building's energy consumption stands at 317.18 kWh/m^2 annually, which can be reduced to 234.34 kWh/m^2 with improvements. Current CO_2 emissions are 185.6 tCO_2e per year, with a 2030 target of 73.7 tCO_2e. A 100-year lifecycle reuse strategy could lower embodied emissions to 270.7 tCO_2e, down from 1,678 tCO_2e, while operational emissions would decrease to 18,372.7 tCO_2e from 169,562.5 tCO_2e.

Given that a significant portion of energy and emission reductions relies on renewable energy sources, two scenarios were analysed: the first one considers the use of photovoltaic panels, while the latter incorporates solar thermal systems.

Proposal A - Installation of 80 photovoltaic panels with Energy consumption 193.33 kWh/m^2/year and an annual emission of 147.1 tCO_2e. In this proposal, electricity costs €32,651.92/year, gas costs €87,831.48, and total emissions are 13,756.7 tCO_2e, representing a 26.2% reduction from the current scenario.

Proposal B - Installation of 34 photovoltaic panels and 80 solar thermal panels with an energy consumption of 125.89 kWh/m^2/year, slightly below the target value, and an annual emission of 104 tCO_2e. In this proposal, electricity costs 39,179.34/year, gas costs €46,144.95/year. The total emissions are 10,074.3 tCO_2e, representing a 45.95% reduction compared with the post-design phase.

The difference between the two scenarios is also evident in the GHGI indicator: 3.646 $kgCO_2e/m^2$ for Proposal A and 2.670 $kgCO_2e/m^2$ for Proposal B, representing a further reduction of 26.77%.

From an economic perspective, the analyses estimate a total building cost of approximately €1,830,644 for the non-optimized project, €2,033,830 for Optimization Proposal A, and €2,171,820 for Proposal B. The differences are mainly related to the renewable energy systems adopted. A precise cost comparison with the existing building is not possible, since material and labor costs at the time of construction differed significantly from current values.

4 Conclusions and Future Perspectives

This design experiment started with a classical approach then focusing on environmental, urban, spatial, structural, technological, and economic factors. Artificial intelligence (AI) played a key role in material selection, by comparing reused project materials against alternative options based on key characteristics such as cost, thermal transmittance (U-value), and embodied carbon emissions (tCO_2), also comparing total GHG emission factor ($kgCO_2eq/m^2$). This data-driven approach helped identify the most suitable materials. AI was also applied to energy optimization, evaluating the existing HVAC systems against more efficient alternatives to select solutions with better performance, lower emissions, and reduced operational costs. Artificial intelligence is now widely recognized as an enabling technology capable of orientating design alternatives against performance objectives, while managing a wide variety of data and reducing the margin of error.

On the other hand, biophilic design helped optimise design solutions by strengthening the relationship between users and natural environment. However, although its potential benefits are supported by a strong theoretical framework, empirical evidence remains limited, and relatively few projects have been assessed using rigorous experimental approaches [11].

This research evaluated how refurbishment interventions that apply an integrated methodological approach based on key principles of circularity, biophilia, and energy efficiency can improve users' well-being, conserve resources, minimize waste and climate impacts in line with international policies. Further studies are needed to explore

the connection between greening buildings and biophilic design for integrated and measurable design solutions [12].

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Fast, Flexible, and Eco-Friendly Modular Construction for Sustainable Built Environment

Mustafa Şahmaran[1](✉), Hüseyin İlcan[1], Sena Nur Öz[2], Metin Karslıoğlu[1], Hocine Siad[3], and Mohamed Lachemi[3]

[1] Department of Civil Engineering, Hacettepe University, Beytepe, Ankara, Turkey
sahmaran@hacettepe.edu.tr
[2] Graduate School of Natural and Applied Sciences, Gazi University, Ankara, Türkiye
[3] Department of Civil Engineering, Toronto Metropolitan University, Toronto, ON, Canada

Abstract. The rapidly increasing global demand for housing, rising construction costs, shortages of skilled labor, and high environmental and economic impacts of conventional construction have highlighted the urgent need for extensive re-search in the field of sustainable construction. In this context, alongside the development of green materials, the adaptation of novel production techniques to the construction sector has gained significant momentum, with the primary objectives of reducing emissions, energy consumption, environmental burden, and overall costs. Considering the need to reshape the built environment in a circular and sustainable manner, this study investigates the development of environmentally friendly, cost-effective, and sustainable mix designs suitable for 3D concrete printing (3DCP) through the use of waste materials (recycled concrete aggregate). Research examines the production of modular structural elements, their rapid on-site assembly, and the required technical infrastructure to enable such applications. Through this approach, circularity within the construction sector can be achieved by reintroducing waste materials into the production cycle as secondary raw materials. The adoption of 3DCP enables the construction of fast, flexible, and eco-friendly structures, while the modular nature of the elements allows construction activities to be carried out largely independent of site conditions. The findings demonstrate that this approach can lead to substantial material savings and significantly reduced construction times, with the structural shell of a 75 m^2 building printed in less than 30 working hours. Overall, the study demonstrates that sustainable production model can be integrated into construction industry through effective use of circular economy–based materials.

Keywords: 3D Concrete Printing · Sustainable Built Environment · Modular Construction · Circular Economy · Waste Utilization

1 Introduction

The rapid growth of the global population, increasing demand for housing and infrastructure, and the renovation or demolition of aging buildings generate billions of tons of construction and demolition waste (CDW) annually worldwide [1, 2]. This waste

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stream accounts for approximately one-third of the total global solid waste generation [3]. The valorization of such a massive material flow through its reintegration into the construction sector as secondary raw materials within a circular economy framework has therefore become increasingly critical. Otherwise, the continued disposal of CDW will lead to further occupation of fertile agricultural lands and intensify soil, water, and air pollution problems [4–6]. The construction sector, already responsible for a significant share of global greenhouse gas emissions and characterized by high energy consumption and environmental impact, faces mounting pressure to adopt transformative solutions [7]. Efficient use of natural resources, reduction of landfill disposal, and the development of environmentally friendly green materials are no longer optional but inevitable pathways toward sustainable development. In addition, the rising cost of construction materials provides strong economic motivation for the high-value utilization of CDW. While earlier applications predominantly relied on low-tech or down-cycling approaches—such as the use of CDW as road subbase or non-structural fill materials—recent research highlights its potential both as recycled aggregate and as supplementary cementitious material (SCM) [8, 9]. Particularly, the introduction of TS EN 197–6 has officially enabled the use of recycled materials as mineral constituents in cement production, accelerating the transition toward value-added recycling strategies. Through such applications, CDW contributes to the development of environmentally friendly, low embodied carbon, cost-effective, and sustainable materials.

Alongside green material development, increasing productivity, minimizing production-related waste, reducing dependency on skilled labor—which is becoming increasingly scarce worldwide—and integrating advanced technologies have driven the digital transformation of the construction industry [10]. Within this context, additive manufacturing, commonly referred to as 3D concrete printing (3DCP), has emerged as a promising alternative production model. This technology fabricates structural elements layer by layer by extruding fresh concrete filaments through a nozzle, following a pre-defined digital toolpath derived from a 3D model. By eliminating conventional formwork, 3DCP enables the realization of geometrically complex and architecturally flexible designs [11]. Since formwork operations constitute a substantial portion of construction time and cost, the reduction or elimination of formwork provides considerable economic and operational advantages [12]. Compared to traditional construction methods, 3DCP offers significant benefits, including improved cost efficiency, faster construction speed, reduced labor requirements and labor-related errors, enhanced occupational safety, and lower material waste generation during execution [13–16]. Consequently, real scale buildings are increasingly being constructed worldwide, while the integration of standards and guideline documents into national regulatory frameworks is still in its early stages.

For 3DCP applications, two primary production strategies exist: on-site printing and off-site prefabricated (modular) manufacturing. The selection between these approaches depends on several factors, including equipment capability, site conditions, environmental exposure, architectural requirements, and logistical constraints. Although on-site applications are currently more widespread, off-site prefabricated and modular production has gained increasing attention. This approach allows uninterrupted production in controlled indoor environments, independent of adverse weather conditions

such as wind, precipitation, extreme temperatures, and humidity fluctuations [17, 18]. It also eliminates frequent printer transportation—particularly critical for gantry-type systems—thereby reducing mechanical wear and operational risks. A stable supply chain, improved quality control, and minimized environmental exposure further enhance technical reliability. However, modular 3DCP introduces new research challenges, particularly regarding joint detailing and structural performance [19]. Comprehensive investigations are required to ensure that modular systems can achieve mechanical performance comparable to monolithic on-site printed walls. Additionally, careful consideration must be given to transportation and assembly processes, as cracking or damage during handling may adversely affect structural integrity [20, 21]. If these concerns are systematically addressed through design optimization and performance validation, prefabricated modular 3DCP could enable fast, flexible, and environmentally responsible construction for a sustainable built environment. Furthermore, such systems inherently support the "design for deconstruction" principle emphasized in international circular economy policies by facilitating disassembly, reuse, and material recovery at the end of service life.

Although the development of green materials tailored for 3DCP systems is widely studied in the literature, research on prefabricated and modular 3DCP applications remains limited. This gap constitutes the primary motivation of the present study. Additionally, the urgent global demand for rapid yet sustainable housing solutions further underscores the importance of this research. Within the scope of the study, a 75 m^2 building was designed and modularized for 3DCP production. Recycled CDW was utilized as a replacement for natural aggregate in the printable concrete mixture, and critical considerations regarding production, transportation, and assembly were systematically evaluated. By integrating circular material utilization with modular additive manufacturing, this study contributes to the current state of the art by (i) providing design and production guidelines for modular segmentation of small-scale housing units, (ii) identifying transportation- and assembly-related risks, (iii) advancing the integration of circular economy principles with digital construction technologies. Through this integrated approach, the research aims to support the transition toward low-carbon, resource-efficient, and digitally enabled sustainable construction.

2 Methodology

In this study, a cement-based mixture incorporating CDW-derived aggregates tailored for 3DCP was developed, with detailed mixture proportions provided in Table 1. The primary binder was CEM I 42.5 R cement, while aggregates included recycled concrete aggregate (RCA) below 2 mm—produced by crushing and sieving demolished concrete—and natural aggregates. A superplasticizer (SP) and a viscosity-modifying agent (VM) were incorporated to achieve the desired rheology and reduce segregation. The mixture was designed to ensure adequate extrudability (as demonstrated in the printing trials shown in the subsequent figures) and exhibited a compressive strength of approximately 40 MPa, indicating sufficient mechanical performance for structural applications. Within the framework of developing a fast, flexible, and eco-friendly modular construction model, a 75 m^2 social facility was digitally designed (see Fig. 1) and configured

as a modular structural system. The wall elements were segmented in accordance with prefabricated 3DCP production principles, considering printability, dimensional constraints, handling, transport, and rapid on-site assembly requirements. Both gantry-type and robotic-arm printing systems were evaluated as capable of producing the designed elements (with particular consideration of the geometric constraints and limited build envelope of robotic-arm systems). The scenario focused on key aspects of modular construction—including element design, segmentation, handling, transport considerations, and assembly strategies—highlighting how prefabricated 3DCP components could support fast, flexible, and eco-friendly construction for a sustainable built environment. Selected wall segments were illustrated to demonstrate the mixture's printability and to support the analysis of modular workflows. This approach provides a comprehensive framework for evaluating modular 3DCP construction, combining mixture performance with practical considerations for prefabrication, logistics, and assembly, without implying full-scale realization of the entire facility.

Table 1. Mixture proportion details (kg/m^3).

Mixture	Cement	Sand	RCA	Water	SP	VM	Fiber
	600	600	600	400	6	3	2

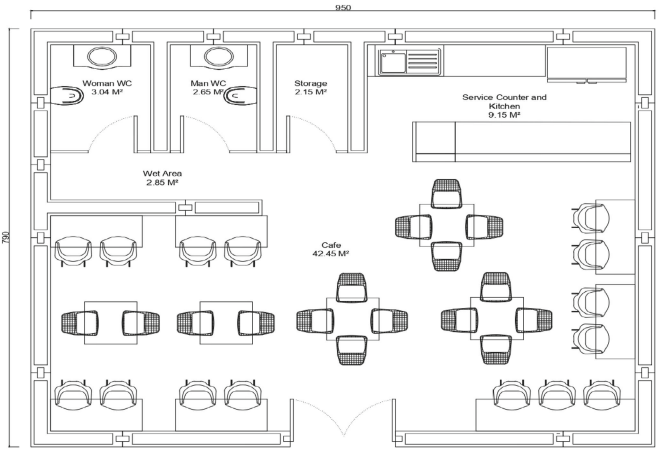


Fig. 1. 75 m^2 modular building plan.

3 Integrated Modular 3DCP Construction Approach

The 75 m^2 social facility was designed to be produced through a modular construction strategy following detailed configuration studies. The primary objective during the modularization process was to minimize the number of modules in order to simplify production, reduce on-site assembly time, and limit the number of connection details and associated labor. At the same time, modules were dimensioned as large as practically feasible while remaining suitable for transportation. Larger modules reduce the number of joints, connection interfaces, potential weak zones, and assembly-related workmanship requirements. In addition to production efficiency, several architectural and technical considerations were considered. These included interior spatial configuration, structural continuity, transportation constraints, and integration of building services. In particular, routing of electrical installations was considered during the design phase; where services were intended to pass through internal wall cavities rather than surface-mounted conduits, module geometry and segmentation were adapted accordingly. To further reduce the number of modules, window openings were planned to be cut after on-site assembly, rather than being printed as separate framed elements during production. This strategy enabled a more compact modular configuration. However, this approach may generate additional material waste during post-processing, which should be considered in terms of sustainability and waste management. Considering these criteria, the 75 m^2 structure was successfully configured using four primary modules, as illustrated in Fig. 2. First, a corner module (Module 1) was designed to define the primary orthogonal geometry. Second, a T-shaped module (Module 2) was developed to provide internal partition connectivity. Third, a long straight wall module (Module 3) was designed to connect corner and T-shaped modules and form the main exterior envelope. Finally, a shorter linear module (Module 4) was introduced to provide architectural flexibility and close remaining wall segments where required. Through this modular logic, the building envelope could be assembled progressively in a rational and repeatable manner.

Based on preliminary production observations and depending on mixture characteristics, it is recommended that printed modules remain undisturbed for at least 2–3 days prior to lifting, and that transportation be conducted after approximately seven days of curing to ensure sufficient early-age strength development. Particular care is required during lifting and loading operations, as printed wall elements—containing lower reinforcement ratios compared to conventional precast reinforced concrete elements—may exhibit relatively brittle behavior. The primary objective during handling is to ensure uniform load distribution along the wall to prevent stress concentrations. Figure 3 presents the 3DCP modular construction workflow, including printing, lifting, placement, service installations, and opening configurations.

During transportation, impact-absorbing materials should be placed beneath the elements, and adequate fastening systems should be employed to minimize movement and vibration. Similar caution is necessary during unloading and positioning on site. Due to their comparatively lower ductility, impact-induced cracking may occur more easily than in heavily reinforced precast systems; therefore, controlled and carefully monitored placement procedures are essential. The step-by-step on-site assembly strategy of the four modules is schematically illustrated in Fig. 4. Excluding transportation time and assuming a prepared foundation, the production and installation of the wall

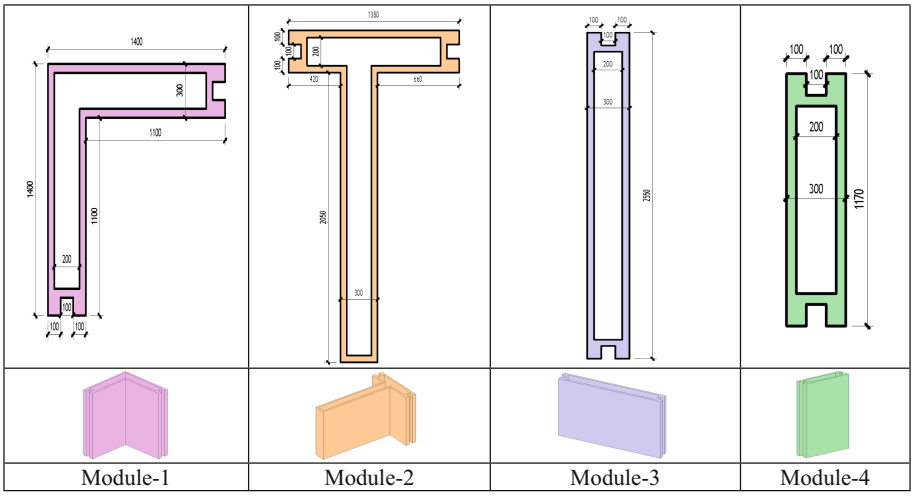


Fig. 2. Building Modules

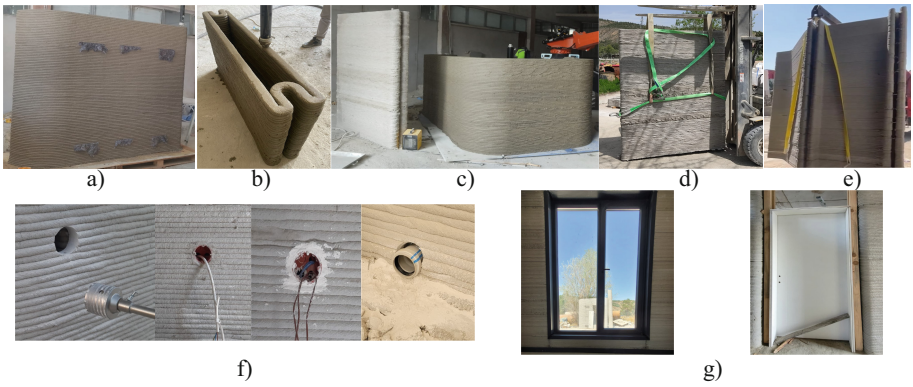


Fig. 3. Representative images of printing (a, b, c), lifting (d), on-site placement operations (e), service installations (f), opening configurations (g)

modules are projected to be completed within approximately 30 h of active operation. Roofing, window installation, and finishing works were not included in this estimation. This time estimation was derived from typical operational parameters of extrusion-based 3D concrete printing systems, including average printing speeds, toolpath lengths, and layer deposition rates. In addition, short intermittent pauses (e.g., approximately 30-min cleaning, maintenance and material conditioning intervals after every 4–5 h of continuous printing) were considered. The overall workflow was further calibrated based on prior on-site experimental printing experiences and reported field implementations of similar robotic and gantry-based systems.

Following installation, a wet joint connection detail (Fig. 5) was adopted to ensure composite action between adjacent wall modules. Based on previous findings [19],

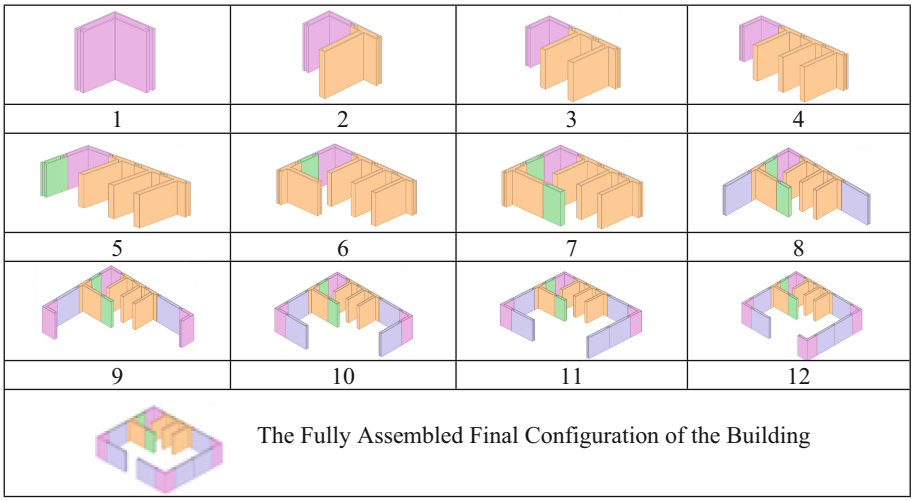


Fig. 4. On-site assembly strategy of 75 m^2 modular building

similar wet joint applications have demonstrated structural performance comparable to monolithic casting, supporting the structural integrity of the modular configuration.

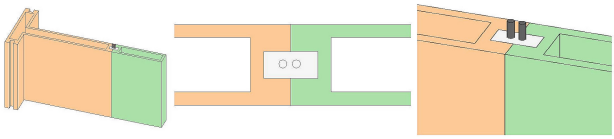


Fig. 5. Schematic connection details of the modular walls

4 Conclusion

In conclusion, this study highlights the potential of a fast, flexible, and eco-friendly modular construction approach as a transformative pathway for a more sustainable built environment. By integrating 3DCP with modular structural design, the proposed system enables rapid production, simplified on-site assembly, and a significant reduction in construction time. The demonstrated ability to complete the structural shell of a 75 m^2 building in very short working hours confirms the efficiency and practical feasibility of this method, particularly in contexts where speed and adaptability are critical. Beyond construction speed, the flexibility of modular design—combined with environmentally conscious material selection—supports a more resource-efficient and resilient building paradigm. The system minimizes material waste, reduces labor dependency, and allows construction processes to be carried out largely independent of site constraints.

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Economic Impact of Digitalization on Prefabricated Façade Modules: A Life Cycle Cost Assessment

Marzieh Zarei(✉) and Riccardo Pinotti

Institute for Renewable Energy/Eurac Research, Bolzano 39100, Italy
marzieh.zarei@eurac.it

Abstract. This study evaluates the impact of digitalization on Life Cycle Costs (LCC) associated with the prefabrication and installation phases of prefabricated façade modules for building retrofit applications. A comparative analysis was conducted between a semi-automated prefabrication workflow, characterized by significant manual operations, and a fully automated workflow implementing advanced automation throughout the evaluated phases, from design and manufacturing to on-site installation. The research focused on a standard opaque façade module with dimensions of 9.6 × 3.4 m as a case study. An LCC assessment methodology was developed to systematically identify and evaluate relevant cost parameters from pre-design measurement to installation of the module. Quantitative data regarding digitalization impacts were collected through structured interviews with prefabricated module manufacturers and suppliers of automated construction machinery, supplemented by literature review, market-based datasets, and technical documentation. The research methodology encompassed three main phases: structuring the analytical framework and selecting comparison parameters, estimating LCC parameters through industry consultation and literature analysis, and performing comparative calculations. Results indicate that comprehensive digitalization of the prefabrication process yields significant economic benefits, resulting in approximately 21% lower total cost for the stages under evaluation and about 53% reduction in execution time per module. The findings indicate the potential economic advantages of digitalized prefabrication technologies for façade retrofit applications under the investigated assumptions and industrial-scale production conditions, while supporting the broader adoption of automated manufacturing processes in the construction industry and contributing to more sustainable building renovation practices.

Keywords: Life Cycle Cost · Prefabricated Façade · Digitalization · Building Retrofit · Automated Construction · Manufacturing Process

1 Introduction

The building sector plays a key role in European decarbonization strategies, making the renovation of existing buildings essential for achieving climate neutrality. In this context, the Renovation Wave strategy aims to at least double renovation rates by 2030

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while promoting more efficient and scalable renovation approaches, which require both significant investment and a faster renovation process [1]. Prefabricated façade retrofit systems have been proposed as a promising solution to accelerate renovation processes while improving construction quality and reducing on-site disruption [2]. At the same time, the growing adoption of digital technologies, robotics, and automated production processes reflects the broader transition toward Industry 4.0 in the construction sector, where digitalization has the potential to enhance productivity and process efficiency [3]. Despite these developments, the economic implications of digitalized construction processes remain poorly quantified. Existing Life Cycle Cost (LCC) tools generally focus on conventional cost categories such as materials and labor and are not designed to capture additional cost drivers associated with digitalization, including digital infrastructure, automated production systems, and advanced surveying methods. As a result, the potential economic benefits of fully automated prefabrication workflows across the façade retrofit supply chain are still not well understood. This study aims to address this gap by assessing the economic impact of digitalization in prefabricated façade retrofit modules through a comparative LCC analysis. The analysis compares a Semi-Automated prefabrication workflow with a fully automated workflow and supports the development of an LCC framework that can capture cost drivers associated with digitalized construction processes.

2 Literature Review

Off-site prefabricated façade retrofit systems have been widely studied as an effective approach for accelerating building envelope renovation by improving productivity, quality control, and safety in construction while reducing renovation time and on-site disruption compared with conventional renovation processes [2, 4]. Recent studies highlight the growing role of digital technologies in supporting prefabricated renovation processes. Digital surveying techniques such as point-cloud acquisition allow accurate capture and processing of existing building geometry, which is important for designing prefabricated façade modules that fit existing structures [2]. These techniques support digital workflows while reducing both process time and costs [5]. In addition, Building Information Modelling (BIM) supports the integration of design, manufacturing, and construction processes by enabling digital information exchange, production planning, and coordination across project stages [6]. Scan-to-BIM workflows allow the automatic generation of digital building models from point-cloud data, improving modelling efficiency and reducing errors compared with traditional manual modelling processes [7]. In prefabricated construction, production lines typically include automated stations such as cutting, framing, insulation installation, and assembly. Automation technologies such as CNC machines and robotic systems can improve accuracy, productivity, and consistency [4, 8]. Robotic façade installation systems can significantly improve installation productivity, reduce labor demand and installation time compared with conventional crane-based installation methods [9]. Although previous studies have mainly focused on technological developments and productivity improvements in digitalized prefabrication processes, limited research has evaluated their economic implications across the full prefabricated façade supply chain. In particular, the life-cycle economic impacts

of transitioning from conventional semi-automated workflows to fully digitalized and automated prefabrication processes remain poorly quantified.

3 Methodology

This study explores the economic impact of digitalization on prefabricated façade modules used in building retrofit projects. The analysis combines a comparative LCC assessment with a process time evaluation. Two supply chain configurations are compared. The first is a Semi-Automated prefabrication Workflow (SAW), which relies heavily on manual operations. The second is a Fully Automated Workflow (FAW) that applies a higher degree of automation across surveying, design, manufacturing, and on-site installation stages. Figure 1 shows the methodological framework adopted in this study.

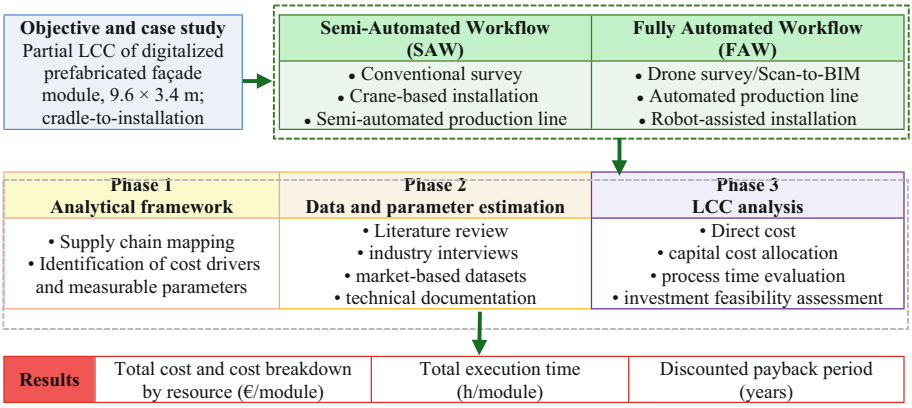


Fig. 1. Methodological framework for comparative LCC assessment of SAW and FAW

3.1 Research Design and Analytical Framework

The main digitalization-related cost drivers were converted into measurable parameters, including labor, waste, machinery investment, energy consumption, and execution time. The case study considers a prefabricated opaque timber façade module for building retrofit applications with dimensions of 9.6 m × 3.4 m, based on a façade element developed within the INFINITE retrofit project [10]. The economic assessment uses a cradle-to-installation system boundary. This includes façade surveying of the existing building, layout generation and 3D modelling, material acquisition, manufacturing of the façade module, and on-site installation. All costs were based on this Functional Unit (FU) for consistent comparison between the two supply chains. Although the assessment does not include operational or end-of-life stages, the study adopts a partial LCC assessment in accordance with ISO 15686-5 to evaluate the economic implications of digitalization across the defined system boundary. The selected cradle-to-installation

scope was considered appropriate because the investigated digital technologies primarily affect surveying, design, manufacturing, and installation processes rather than the operational performance of the façade system. The comparison focuses on evaluating the influence of digitalization within the defined prefabrication process.

3.2 Data Collection and Parameter Estimation

Input data for the economic assessment were obtained from multiple sources to support the robustness and reliability of the cost model. Most parameters were derived from scientific literature, market-based construction cost databases, technical documentation, and national statistical sources, providing information on labor costs, waste generation ratios, installation productivity, economic indicators, and energy prices. In addition, structured interviews with key industrial stakeholders, including façade system designers and automated production technology suppliers, were conducted to gather data on investment costs, operational characteristics of automated production lines, and modelling time requirements. Because publicly available industrial data for automated façade systems remain limited, interview-based estimates were primarily used for automation-related parameters and cross-checked against literature sources and technical documentation to improve robustness. Although the number of interviewees was limited, they represented key actors directly involved in automated façade production and technology supply. The collected information supported the quantification of process times, labor requirements, energy consumption, and investment costs for both workflows, forming the basis for the calculation of resource-related costs.

Table 1 summarizes the key parameters used in the cost model together with their corresponding data sources.

Table 1. Input data and assumptions for LCC calculation

Parameters	SAW	FAW	Source
Geographical context	Italy		Assumption
Real discount rate (%)	0.4	0.4	[11, 12]
Data acquisition (h/m^2)	0.15	0.038	[13]
Data processing (h/m^2)	0.47	0.073	[13]
3D modeling (h/m^2)	0.07	0.35	Industry, [13]
Survey tool / life (years)	Total station, 12	UAV system, 6	[14, 15]
Material costs	Common material cost for both		[16]
Waste generation ratio (%)	6%	3%	[17]
Production line investment (€)	6,500,000	11,000,000	Industry
Production line maintenance (%)	10%	10%	Industry
Production workers (Number)	25	7	Industry
Energy use (MWh/year)	350	441	Industry
Equipment life (years)	25	25	Industry

(*continued*)

Table 1. (*continued*)

Parameters	SAW	FAW	Source
Installation equipment	Crane	Robot	[9]
Installation maintenance (%)	Not owned	10%	[9]
Installation workers (Number)	6	4	[9]
Installation time (h/m^2)	0.5	0.22	[9]

3.3 Life Cycle Cost Calculation Approach

The economic assessment was carried out using the LCC approach in accordance with ISO 15686-5. Costs were classified into two main categories: direct and allocated costs. Direct costs, such as material and labor costs, can be calculated directly for the defined FU. Allocated costs correspond to capital-intensive resources shared across multiple production cycles, such as production machinery, robotic systems, and digital surveying equipment. The allocation of capital costs was calculated assuming an annual production capacity of 3215 façade modules for both SAW and FAW configurations. This assumption was derived from industry interviews and manufacturing line productivity data. The assumed production capacity reflects a large-scale industrial retrofit scenario with continuous operation of the automated production line. Since capital-intensive automated systems strongly depend on production volume, the economic performance of the defined configurations may vary under different production scales. As capital assets are used across multiple years and production cycles, investment costs were annualized using the Capital Recovery Factor (CRF) [18] and distributed across the annual production capacity. In addition to the cost calculation per FU, an investment feasibility analysis was conducted to evaluate the economic viability of investing in an automated production line. The analysis compares the additional capital investment required for the fully automated production line with the operational cost differences between the automated and semi-automated production lines. The additional investment associated with the automated production system was considered as an initial cash outflow in year zero. Annual cash flows were calculated by considering operational cost differences, including labor cost savings as well as additional maintenance and energy costs. These annual cash flows were discounted using the real discount rate assumed in the study and accumulated over the analysis period. The discounted payback period was defined as the year in which the cumulative discounted cash flow becomes positive. The analysis was carried out over a 25-year period corresponding to the assumed service life of the production equipment. To conduct the LCC analysis, an existing tool [19] was used and adapted to reflect the characteristics of digitalized prefabrication processes. The framework was expanded to include resources associated with digital technologies and automated manufacturing, such as robotic production equipment, digital surveying tools, and related energy consumption, in addition to conventional resources like materials, labor, and transportation. This adaptation allows a more comprehensive representation of digitalized prefabrication supply chains and their economic implications across life

cycle stages. The cost modelling follows an activity-based approach, where the prefabricated façade supply chain is divided into individual activities. For each activity, the required resources are identified and quantified, and costs are calculated based on their consumption. This structured classification enables a consistent evaluation of cost drivers in both SAW and FAW.

4 Results

The analysis compared two supply chain configurations defined in the methodology: a SAW and a FAW. Results are expressed per FU of one prefabricated façade module. The FAW results in a lower overall cost per module compared with the SAW. The total cost decreases from €8651 per module in the SAW to €6833 per module in FAW, corresponding to an overall cost reduction of approximately 21%. Figure 2 highlights the main cost drivers across the analyzed stages. Material acquisition represents the largest share of total costs in both scenarios, accounting for approximately 67.8% in FAW and 53.7% in SAW. In the manufacturing stage, equipment and robotic systems represent a larger share of costs in the FAW, while in the SAW labor costs dominate the manufacturing stage. A similar pattern is observed in the installation stage, where labor represents a significantly higher share of costs in SAW, whereas FAW shows a reduced labor contribution due to the use of automated installation technologies. SAW requires more manual surveying effort, whereas FAW requires more detailed 3D modelling for automated production.

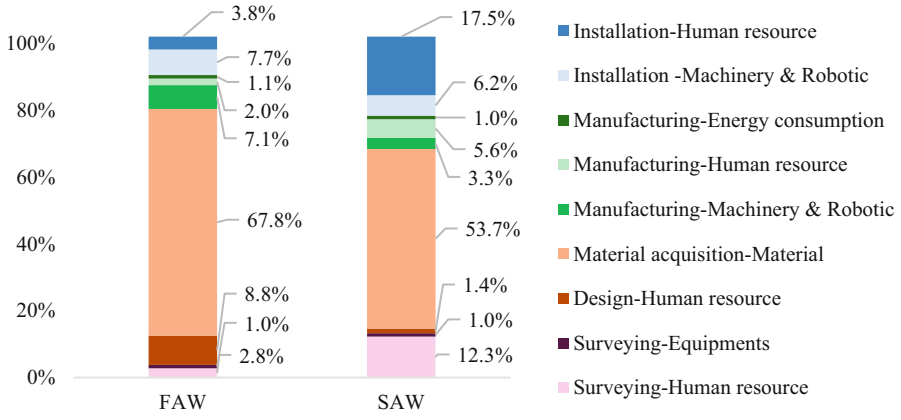


Fig. 2. Cost breakdown for FAW and SAW (percentage)

The total execution time was evaluated, and the results show a decrease from 17.5 h in SAW to 8.2 h in FAW, mainly due to automation in the installation stage. Investment feasibility analysis was conducted, and the results indicate that the additional capital investment required for the automated production line can be recovered within approximately 7.5 years, assuming a 25-year service life of the production equipment.

5 Discussion and Conclusions

The results suggest that automation can significantly improve both the economic performance and process efficiency of prefabricated façade production. The lower costs observed in the FAW mainly result from changes in the supply chain cost structure. In the SAW, labor-intensive activities account for a large share of total costs, particularly during manufacturing and installation. In contrast, the FAW shifts costs toward machinery and automated systems while reducing labor requirements and improving process efficiency. Automated installation technologies reduce the number of workers required and shorten installation time, contributing to the significant time and cost reductions observed in the FAW scenario. The results also highlight the importance of production scale for the economic viability of automation. Since automated systems require high capital investment, their economic advantage increases when production volumes are sufficient to distribute investment costs across multiple façade modules. Lower production volumes would weaken this advantage. Therefore, digitalized prefabrication appears economically promising, particularly for large-scale retrofit projects under the assumptions considered in this study. Beyond economic efficiency, digitalized prefabrication may also support broader sustainability objectives in building retrofit practice. Improved production accuracy and reduced material waste can contribute to more resource-efficient construction processes, while faster and more industrialized renovation workflows may facilitate the large-scale implementation of energy retrofit strategies aligned with circular and low-carbon construction goals. Among the investigated parameters, labor costs, annual production volume, investment costs of automated systems, and maintenance costs have the strongest influence on the economic outcomes. In particular, the reported cost reduction and discounted payback period are sensitive to assumptions regarding industrial-scale production capacity and labor intensity. Since labor is one of the most cost-intensive resources, economic outcomes may vary across different geographical contexts and wage levels. The findings should be interpreted within the context of the selected case study and assumptions adopted in the analysis. The assessment focused on the production and installation stages of the prefabricated façade supply chain rather than a complete building life cycle evaluation, since the study specifically investigates the economic implications of digitalization within surveying, design, manufacturing, and installation processes. In addition, several parameters related to automated production systems were estimated through structured interviews with industry stakeholders due to the limited availability of publicly accessible industrial data. Consequently, the reported cost reduction and payback period may vary under different façade typologies, labor markets, and production scales. Future research should investigate multiple case studies, regional conditions, and sensitivity analyses to further evaluate the robustness and generalizability of the results.

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Structural Steel Reuse: The Logistical Dimension of a Technical Challenge

Raffaele Cucuzza[1](✉), Jerome F. Hajjar[2], Gian Andrea Rassati[3], and Stergios-Aristoteles Mitoulis[1]

[1] Centre for Global Infrastructure Resilience, The Bartlett School of Sustainable Construction, University College London, London, UK
r.cucuzza@ucl.ac.uk

[2] CDMSmith Professor, University Distinguished Professor, and Department Chair, Department of Civil and Environmental Engineering, Northeastern University, Boston, USA

[3] Department of Civil and Architectural Engineering and Construction Management, University of Cincinnati, Cincinnati, OH, USA

Abstract. Over the past decade, the scientific community has increasingly recognized reuse as one of the most promising strategies for transforming the building sector in line with circularity and sustainability principles. Reclaimed structural steel has emerged as a valuable solution with the potential to transform the decarbonization pathway of the construction industry. Despite the limited maturity of current research on automated design tools under conditions of limited material availability, major logistical challenges remain the primary obstacle. These include supply-chain constraints and the complex coordination among multiple stakeholders, which collectively reduce the attractiveness of transitioning from steel recycling to steel reuse. This study focuses on interdisciplinary logistics–technical dimensions in structural steel reuse, to accelerate adoption and overcome persistent systemic inertia in a contested landscape. This approach underscores the necessity of establishing a new supply-chain model in which additional actors are introduced to address critical questions: What is the quantity of steel that can realistically be recovered from deconstructed buildings? How can the appropriate quantity of steel be made available upon request while coordinating diverse—and at times conflicting—interests, such as client and designer demands (technical) versus the supply capacities of demolition and stockholding contractors (logistical)?

Keywords: Reusing Steel · Supply Chain · Embodied Carbon · Artificial Intelligence

1 Introduction

The construction sector is the largest consumer of raw materials. It accounts for 50% of the total material use in Europe [1] alone and 25%–40% of the total CO2 emissions globally [2]. The building construction drives current energy consumption and greenhouse gas (GHG) emissions, representing 36% of total energy use and 37% of the global

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GHG emissions, respectively [3]. Approximately, 10% of these emissions are carbon emissions caused by the production of materials in buildings [4]: The average embodied carbon emissions associated with new buildings are approximately 600 $kgCO_2eq/m^2$, with nearly 70% occurring upfront during the building production and construction stages. Besides, construction activities produce the highest amount of waste among all other sectors [4]. As a result, the construction industry is under more scrutiny than ever to reduce resource consumption, construction, and demolition-related waste while encouraging reusing practices unquestionably represent an efficient path to promote Circular Economy [5]. At the heart of a circular economy lies the fundamental principles of reducing waste generation and maximising the service-life of products and materials [6]. Thus, there is a unique incentive to use existing materials in the construction industry by reusing structurally functional parts (re-using) or the use of raw materials as components to produce new structural elements (recycling). Based on the waste hierarchies, reuse is vastly superior to recycling. Specifically, the environmental benefits of reusing structural steelwork reside in the low carbon intensity of 50 $kgCO_2$ eq./t compared with a sector average of 1740 $kgCO_2$ eq./t for new steelwork [7]. As a consequence, adopting reclaimed steel leads to a significant reduction in virgin material providing huge benefits in terms of sustainability aspect. Despite this, most construction and demolition waste recovery occurs through recycling rather than reuse. Steel is a circular material, with about 85% recycled globally at the end of its first life. In the EU, approximately 90% of scrap steel is recycled but only 5% reused, highlighting a significant gap. For example, in the UK, a leader in decarbonisation, steel reuse remains limited, representing only 8–11% of steel recovered from demolition [8].

This study aims to systematically identify, classify, and assess barriers to steel reuse to determine critical system bottlenecks. It also proposes a prioritization framework to distinguish barriers that significantly constrain market upscaling from those addressable in later phases. This classification supports the development of an enhanced supply chain configuration that mitigates key bottlenecks through the introduction of a dedicated Service Centre coordinating entity to facilitate complex information exchange among stakeholders.

2 Distinguishing the Technical and Logistical Dimensions of Steel Reusing

Based on the literature, researchers and steel associations consistently identify six major barriers to reuse [9]: (1–2) social and psychological factors related to limited reuse markets and perceived risks in specifying reused materials; (3–4) timing and cost issues associated with deconstruction and transportation logistics; (5) certification procedures (e.g., Material Passports); and (6) technical challenges during design and construction. Recent stakeholder surveys highlight supply chain dynamics and reused steel availability as the most critical barriers [10, 11]. Accordingly, a clear prioritization strategy is required, beginning with grouping these barriers into two main classes: (1) technical and (2) logistical dimensions of the steel reuse challenge.

2.1 The Technical Dimension

The technical dimension mainly accounts for all the activities occurring during the design and construction phases as well as all the certification procedures. The technical dimension of the steel reusing challenge can be summarized in the following key points.

Limited stock availability requires resolving complex allocation mathematical problems within stock-constrained design frameworks. In recent years, researchers have developed computational tools integrating cutting-stock and assignment algorithms into early-stage design optimization to manage this complexity. These methods have been applied to various structural typologies, including trussed frames, gridshells, and diagrid systems, often relying on optimization, form-finding, or AI-based frameworks using assumed or randomly generated stock inventories. However, real-world implementation remains limited, particularly in balancing computational efficiency with structural analysis accuracy. Furthermore, limited research has integrated cradle-to-cradle life-cycle assessment (LCA) methods accounting for global warming potential (GWP) from raw steel production across building life-cycle stages A1–D. Many tools also show strong performance for specific typologies but limited generalizability across structural systems. Design flexibility depends on available salvage components, while higher reuse rates may require trade-offs in structural efficiency, increasing weight and architectural constraints. Table 1 summarizes recent stock-constrained optimization tools.

Deconstruction processes, constructability considerations, and erection feasibility associated with the reuse of structural components remain among the most significant technical challenges in steel reuse practices. Time constraints frequently render deconstruction less economically attractive than conventional demolition methods. Furthermore, the majority of existing steel buildings are characterized by joints that are either inaccessible or irreversible, thereby complicating design-for-deconstruction strategies. Evidence from successful case studies highlights the critical role of systematic numbering and labeling of reusable components in ensuring project efficiency and overall success. These challenges prompt critical reflection on the importance of promoting design-for-deconstruction practices in the development of future building designs.

Material/product passport and **reusing marketplace digitalization** are well-known as fundamental requirements for steel reusing. As highlighted by Costa in [12], Materials Passports give every material an identity. Each passport is a digital record that consolidates essential information about the material in a centralized, accessible location. By tracking a material's chain of custody, materials passports reduce waste, support better design, and improve reuse rate. They also promote data transparency and traceability, document circularity metrics, measure carbon expenditure and inform decision-making processes. This comprehensive database has been integrated with information on the damage levels of reusable components.

Certification protocols for reusable steel components require time-intensive testing to verify their structural integrity. Factors such as corrosion and accumulated mechanical stress may significantly alter material properties, complicating reliable structural assessment. Current research is increasingly integrating advanced digital technologies and image-based detection methods to automate portions of pre-demolition audits and reuse assessment procedures, thereby reducing costs and improving reliability. AI-based

Table 1. State of the Art of the Stock-Constrained Design Optimisation Tools

Reference	Year	Design Variables	Algorithm	AI	LCA	Case Study	Carbon Savings	Assign. Problem	CS Problem
[13]	2019	Geometry Topology	MILP/NLP	no	yes	Truss	56–63%	yes	no
[14]	2020	Size	MILP/NLP	no	yes	2D frame	35%	yes	yes
[15]	2024	Size	GA	no	yes	Truss	36–63%	no	yes
[16]	2024	Size Geometry	NSGAII	no	no	Gridshell	–	no	yes
[17]	2025	Size Geometry	ILP	yes	yes	Gridshell	37–57%	yes	no
[18]	2025	Size Geometry	GA	no	yes	Gridshell	30–50%	yes	no
[19]	2026	Size Geometry	MILP	no	yes	2D frame	64–67%	yes	no

reusability prediction models can be trained on structural images to support rapid preliminary condition assessments, significantly reducing the time required for conventional non-destructive testing**.**

There are currently **no standardized design rules** specifically applicable to the reuse of reclaimed steel components on a global scale. Although certification and execution protocols, as well as guidelines for the assessment of existing structures, have been developed, these typically vary from country to country, thereby limiting the scalability of the reuse market.

2.2 The Logistic Dimension

The logistic dimension of the steel reusing challenge mainly refers to the complex interaction of activities between the different actors of the supply chain. Below, we summarize the main issues which refer to logistic aspects.

Optimizing the alignment between demand and supply timing within reuse supply chain operations is essential for ensuring efficient material recovery and deployment. Unlike newly produced steel, the availability of reusable steel is highly dependent on the careful, damage-free demolition and dismantling of existing structures, with the majority of reusable steel currently originating from demolition activities. Consequently, timely access to reliable information regarding available steel stock—whether from single or multiple sources, depending on project requirements—is critical for supporting design decision-making within client-commissioned projects. In particular, design teams must be able to assess the feasibility of integrating reused steel components during the early stages of project development. This process becomes significantly more complex when the required stock is not readily available in storage but instead depends on the disassembly of donor buildings, thereby introducing additional uncertainties related to scheduling, logistics, and material availability.

Availability of comprehensive market data plays a crucial role in improving supply chain efficiency. A systematic mapping of the quantity of reusable steel available on the market—at regional, national, or continental scales—would support more informed sourcing decisions. Such mapping could contribute to reducing transportation costs and optimizing efficiency across the supply chain, including sourcing, fabrication, and refinement processes associated with reused components. Activities of this nature should be undertaken by governmental bodies or accredited third-party entities operating at local or national levels, with the objective of collecting and disseminating reliable information regarding reusable steel stock that is ready for deployment. An example of such an initiative is provided by the Efestos Hub, which represents one of the first organizations to develop a detailed mapping (called e-maps) of potential reusable steel stock and donor buildings within the United Kingdom. Based on preliminary estimates, 1,073 buildings have been mapped, corresponding to a potential reusable steel stock of approximately 1.9 Mt. and an estimated CO_2 savings of 2 Mkg.

Institutional coordination mechanisms are necessary to facilitate collaboration among the various stakeholders involved. Certified entities capable of acting as coordinating bodies could support communication and alignment among all actors in the process. In particular, these entities should effectively harmonize the requirements of clients (e.g., designers and construction companies) with those of stockists and fabricators. This entity should support the stockholder or the client in the early review of the range of reusable steel components available, and suggest fabricators/steel erectors potentially interested. By facilitating this alignment, it becomes possible to identify the most suitable stock for specific design and construction needs, while simultaneously reducing delays and improving overall project delivery timelines.

3 A New Supply Chain: A Service Centre-Like Coordination Entity

Following the identification of barriers to steel reuse, it is essential to prioritize those requiring immediate intervention. Beyond the technical challenges outlined in Sect. 2.1, the main limitation to reuse market development lies in uncertainties affecting the current supply chain. While advances in design optimization tools, certification, and product traceability represent important enabling measures, they remain insufficient to address the complex logistical challenges associated with effective stakeholder communication and coordination. For clarity, reference is made to consolidated reuse supply chain models reported in Fig. 1. Among the available configurations, the model adopted here assumes that ownership of reclaimed steel is retained by the stockholder, who purchases materials from demolition contractors and subsequently sells them on the open market.

Within this supply chain configuration, the stockholder is responsible for receiving reclaimed steel from demolition contractors, supplying materials to steel contractors and, when required, directly to erectors, while coordinating with the main contractor. The main contractor manages on-site erection and procures stock to meet designer and client requirements. The accumulation of these responsibilities often leads to operational overload, where delays in communication or coordination can result in significant additional costs. In other words, structural steel reuse depends not solely on improved design

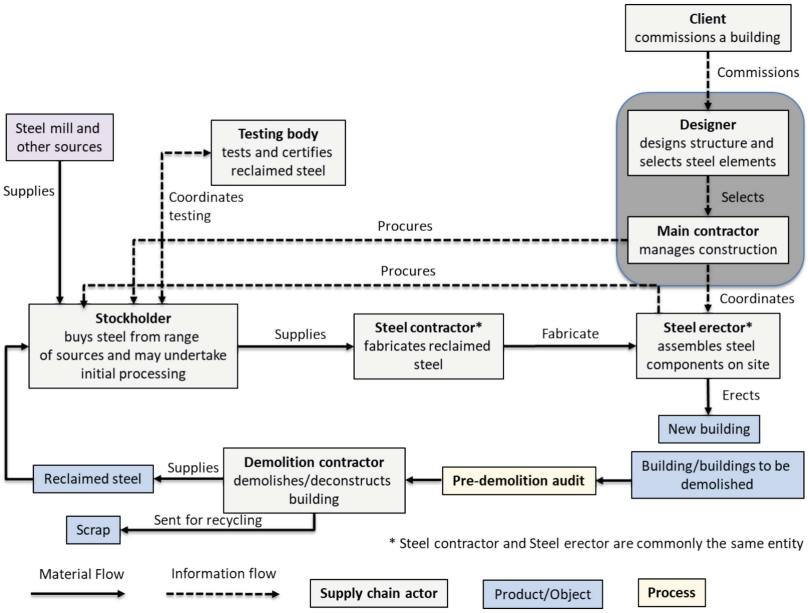


Fig. 1. Current Stockholders-driven supply chain of reusing steel.

tools or advanced rapid damage-detection technologies, but critically on a coordinated, information-driven supply chain centred on a dedicated logistics intermediary.

Figure 2 presents a Service centre–driven supply chain model that centralises coordination and enables iterative, data-driven matching of supply and demand, addressing the key logistical constraints limiting structural steel reuse.

In the proposed model, the introduction of an additional actor—referred to as the Autonomous Agentic Service Centre—plays a central role in coordinating reuse supply chain operations. This entity functions as a hub operating at regional, national, or continental scales, with the objective of mapping, in near real time, the availability of reusable steel and organizing marketplace information within a dynamic database.

An agentic AI platform would process real-time data from steel contractors and stockholders, assigning targeted marketplace search tasks to virtual AI agents to identify the most suitable stock for a given project. The Agentic Service Center platform would also generate a Digital Material Passport containing information on stock provenance and the economic and sustainability costs associated with certification, transportation, and fabrication. Each AI agent would be trained to optimize technical, sustainability, and economic objectives according to client-defined preferences and priorities. The database is continuously updated with data provided by stockholders and steel contractors, who remain responsible for the storage, certification, and fabrication of reclaimed components. The Call Centre can be activated by designers or main contractors during early design stages to identify suitable stock that meets project requirements and client expectations. This activation process is inherently iterative (see Fig. 2), enabling continuous

evaluation of alternative stock options to accommodate design revisions, architectural modifications, and site-specific constraints until an acceptable solution is achieved.

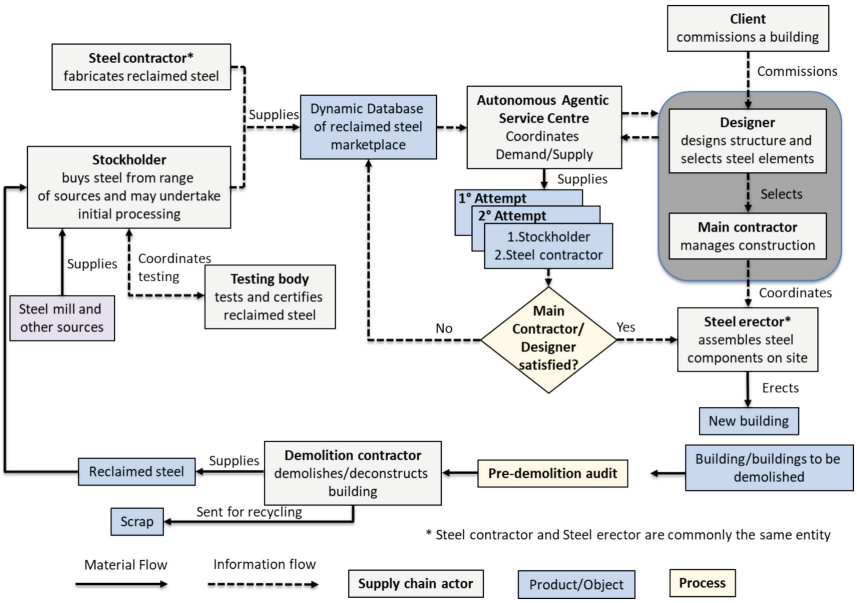


Fig. 2. Agentic Service Centre–driven model of the reusing steel supply chain

4 Conclusions

In this study, the authors provide a comprehensive analysis of the current barriers to steel reuse, with the objective of improving the understanding of the most critical challenges hindering large-scale implementation. Among the identified barriers, the logistical dimension emerges as one of the principal bottlenecks within the reuse process, highlighting the need for an intermediary entity capable of coordinating the complex flow of information among the various stakeholders involved. To address this limitation, the authors propose a novel supply chain model as an alternative to conventional, well-established frameworks. The proposed model introduces a new actor—referred to as Autonomous Agentic Service Centre Coordination Entity—responsible for collecting and analyzing information from the reuse marketplace, facilitating interactions among stakeholders, and accelerating the responsiveness of supply availability to meet design and construction requirements.

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The Identification of Barriers and Potential Drivers for the Implementation of Digital Product Passports (DPPs) for Social Housing in Scotland

Michael Tong[1(✉)], Craig Thomson[1], Shefali Chauhan[1], Abraham Zhang[2], Ming Lim[2], and Guo Chen[2]

[1] Glasgow Caledonian University, 70 Cowcaddens Road, G4 0BA Glasgow, UK
M.Tong@gcu.ac.uk

[2] Adam Smith Business School, University of Glasgow, 2 Discovery Place, Glasgow G11 6EY, UK

Abstract. The construction industry is among the largest sectors that generate one-third of the global greenhouse gas emissions. Therefore, it is essential to integrate a circular economy approach to drive transformation in the construction sector. The introduction of Digital Product Passports (DPPs) can accelerate this transformation by offering a digital framework that integrates material intelligence, demountable design, and systematically embedding environmental performance assessments of building materials from procurement, through construction and asset management to facilitate future re-use. A DPP is an electronic platform that registers, processes, and shares data for products at material, component, product, system, and building levels to enhance product traceability and supply chain transparency. The implementation of DPPs in the construction industry will improve resource circularity, reduce emissions, and strengthen supply chain governance. It forms a key regulatory element of the EU's Circular Economy Action Plan, mandating the electrical, textile, packaging, and construction industries to provide implementation milestones by 2026. This study aims to identify the barriers and potential drivers to implementing DPPs by conducting a focus group and semi-structured interviews with participants from different functions within a large Social Housing organisation which is at the early stages of their exploration of circular construction and the adoption of DPPs. The initial findings suggest that there are significant challenges, especially political and economic barriers. However, significant tangible benefits emerged in terms of procurement and financial leverage for funding. The findings from this paper could offer fresh perspectives for organisations ready to embark on a path towards Circular Construction.

Keywords: Circular Construction · Construction Industry · Digital Product Passport · Social Housing · Supply Chain

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1 Introduction

1.1 DPP in Circular Construction

The construction industry plays a significant role in global resource use and carbon emissions. It accounts for about 40% of energy use and generates nearly one-third of greenhouse gas emissions [1]. Improving resource efficiency and reducing environmental impacts throughout the building lifecycle are critical for the sector's transition to a circular economy. In this context, Digital Product Passports (DPPs) have emerged as key digital tools supporting circular construction supply chains. By recording and integrating product lifecycle information, DPPs enable the traceability of building materials from production to end-of-life. Existing research recognises that DPPs are more than information tool ets; they serve as digital infrastructure supporting the circular economy. They link product lifecycle information, supply chain participants, and circular reuse practices [2]. By integrating material properties, environmental data, and usage information, DPPs enhance transparency and stakeholder collaboration and provide data-driven support for decision-making in the design, construction, and demolition phases.

1.2 Drivers of DPP

Existing research indicates that the adoption of DPP within the construction supply chain is driven by multiple factors, which can be broadly categorised into three dimensions: policy drivers, technological advancements, and socioeconomic incentives. Firstly, policy frameworks serve as a crucial catalyst for DPP development. In recent years, the European Union has introduced policies such as the European Green Deal and the Circular Economy Action Plan (CEAP) to encourage enterprises to enhance the transparency of product environmental information and disclose lifecycle data [3, 4]. These policies aim to reduce greenwashing and strengthen environmental accountability in supply chains by establishing mechanisms for product information disclosure and traceability [5, 6]. Furthermore, policy financial instruments—such as subsidies and sustainability-linked loans—can facilitate DPP system implementation by mitigating enterprises' investment risks in digital infrastructure [7]. Secondly, the digitalisation of the construction industry and advancements in material technology create essential conditions for implementing DPP. With the widespread adoption of Building Information Modeling (BIM), the Internet of Things (IoT), and data management systems in construction, the collection and sharing of building lifecycle data have become increasingly feasible [8, 9]. These digital capabilities enable enterprises to more effectively record and manage product information, thereby providing the technological foundation for DPP applications. In addition, the enhanced performance of recycled materials has significantly broadened their scope of application in construction, improving thermal insulation, soundproofing, environmental sustainability, and cost-effectiveness [10]. Comparative analyses between new and traditional materials, along with feasibility studies, have driven demand for DPP. Finally, socioeconomic factors also drive corporate adoption of DPP systems. Research indicates that sustainable construction typically reduces operational energy consumption and lowers waste disposal costs [11]. Concurrently, growing demands from investors, customers, and regulators for transparency in environmental performance are driving

companies to adopt digital management systems that enhance supply chain visibility [12].

1.3 Barriers to DPP

Despite the significant potential of DPPs to drive circular transformation in the construction sector, their implementation faces multifaceted barriers encompassing policy, technological, and market or societal challenges. Firstly, at the policy level, fragmented regulatory frameworks may increase the complexity of implementing DPP for businesses. Existing environmental regulations, building codes, and safety standards often lack coordination, resulting in higher costs for businesses that must comply with multiple regulatory requirements [13, 14]. At the same time, without sufficient policy funding, small and medium-sized enterprises (SMEs) may struggle to bear the investment required for digital system development [15]. Secondly, technological and data challenges present significant barriers. Many construction projects lack comprehensive lifecycle data, particularly during the material reuse and end-of-life management phases [16]. The absence of unified data standards across different digital platforms further complicates system integration [17]. Furthermore, existing digital tools often prioritise environmental metrics while offering limited capacity to assess economic performance, making it difficult for businesses to comprehensively evaluate the financial viability of circular strategies [18]. Finally, market and societal factors also constrain the adoption of DPP. Implementing DPP systems typically requires significant upfront investment, including certification, testing, and the development of digital infrastructure [12]. At the same time, public awareness of circular building concepts remains limited, and consumer interest in sustainable housing does not necessarily translate into actual market demand, with conflicting perceptions among different consumer segments [19]. Furthermore, the highly fragmented supply chain structure within the construction industry complicates information sharing and collaborative management among diverse stakeholders [20].

1.4 An Exploratory Study of Social Housing in Scotland

The net-zero agenda is widely recognised. However, it is imperative to adopt circular economy principles, wherein buildings are conceived to be assembled, utilised, disassembled, and repurposed as necessary. This approach not only aligns with the net-zero agenda but also prioritises waste reduction in building design. This research study goes 'beyond' net zero by addressing carbon reduction through a circular economy approach, which will not only impact the built environment but will also relate to biodiversity, human and ecosystem health to ensure and maintain a just society and flourishing ecological systems across Scotland. The construction sector has been identified as one of eight sectors with the highest circularity potential. The role of social housing providers in Scotland is vital to a just transition that ensures everyone can afford the energy they need to live comfortably, which requires a systems view that incorporates a circular approach. In order for this to be realised, the development of a circular supply chain at the city level will need to be examined. Moreover, digitalisation and data management can support better tracking and management of materials, thereby improving decision-making. Through the examination of solutions such as the DPP, techniques such as cost-benefit

analysis could be used to establish evidence that will enable positive change. The aim of this research study is to contribute towards a DPP-enabled circular supply chain for social housing by identifying the drivers and barriers to circularity and providing recommendations for transitioning towards DPP-enabled circular supply chains. While existing research increasingly explores the potential of DPP within circular supply chains, empirical application studies within the construction sector remain limited, particularly in the social housing domain. Compared with commercial buildings, social housing projects typically require balancing sustainability objectives with housing affordability while navigating multiple factors, including long-term asset management, public policy regulations, and technology implementation costs. Therefore, understanding the implementation conditions and potential impacts of DPP within social housing supply chains is crucial for advancing circular economy practices in the construction industry.

2 Methods and Methodology

This study employed a mixed-methods approach to explore the potential and identify what needs to be done to build a digital product passport (DPP)-enabled circular supply chain, focusing on social housing in Scotland. A systematic review was conducted to map the current state of research, identify key drivers, and categorise the types of barriers to implementing DPP-type circular approaches in the construction sector. The literature review was conducted using Scopus and Web of Science using keywords such as DPP, circular supply chain, built environment, and drivers and barriers. A total of 176 articles were screened based on titles, abstracts, and keywords, resulting in 92 articles included in the review. The literature review provided a foundation for identifying and categorising the drivers and barriers to DPP implementation. This research study primarily focused on qualitative methods. Qualitative and semi-quantitative methods were employed to obtain in-depth insights and structured perceptions from stakeholders. This methodology was chosen to understand the potential and barriers to DPP implementation across organisational roles. The participants were purposively selected from different roles and departments to ensure the representation of key functional areas within the organisation. This research study included one focus group and semi-structured personal interviews from procurement, new build, and finance departments to understand both role-specific and general perceptions of the key drivers and barriers of DPP.

3 Data Collection

3.1 Focus Group

A focus group was conducted with 8 stakeholders who are currently involved in delivering their Sustainability Strategy and who could share their expertise to explore the potential of DPP to enable a circular supply chain. The stakeholders involved in the focus group came from a variety of roles, including Procurement Manager, Contract Management System Coordinator, Finance Manager, Sustainability Officer, Business Improvement Coordinator, Development Manager, Demolition Officer, and Group Investment Lead, among others. The focus group was held in person and lasted around 2 h. The session

was audio-recorded to ensure data collection and subsequent analysis. The focus group began with a short introductory presentation outlining the concept of DPP and its potential role in enabling circular supply chains in the built environment, drawing on past case studies. Each barrier was sub-categorised into 14 sub-barriers (B1-B14), as shown in Table 1, identified from the systematic review, and discussed to capture the group's perceptions of the importance and impact of each to implementation.

Table 1. Barriers and sub-barriers to DPP implementation, used in the focus group.

Barrier Category	Sub-Barriers
Policy and Incentive Barriers	B1: Absence of an Integrated Regulatory Framework for Circular Building Design and Product Governance
	B2: Regulatory Inconsistency and Conflicting Standards
	B3: Insufficient Economic Stimulus Measures
Data and Technology Barriers	B4: Incomplete Life Cycle Data and Traceability Gaps
	B5: Data Lacks Standardisation and Format Consistency
	B6: Data Inaccuracy
	B7: BIM/LCA Tools Do Not Fully Work Together
	B8: Limited Decision-Support and Integration of Economic Factors in the Related Tools
Market and Society Barriers	B9: Inadequate Corporate Financial Evaluation Frameworks
	B10: Long Payback Periods and Uncertain Added Value of Digital Information Platforms
	B11: High Costs of Green Transformation and Certification
	B12: Poor Knowledge Sharing and Ad-hoc Project Basis
	B13: Lack of Cross-Entity Collaboration Mechanisms
	B14: Conflict between Data Sharing and Privacy

3.2 Semi-Structured Personal Interviews

Semi-structured personal interviews were conducted with 3 key stakeholders from the procurement, new-build development, and finance departments. These roles were selected to capture department-specific perspectives on the benefits, feasibility, potential challenges, and operational implications of implementing DPP. These interviews were aimed at evaluating in-depth insights into participant's perspectives based on their roles in the organisation. The interviews were conducted while maintaining consistency across key discussion themes by using 8 common and 2 role-specific multiple-choice questions on the following. The interviews were conducted individually to allow participants to provide detailed responses and lasted approximately 30 min, with each interview audio-recorded with consent to ensure accurate data capture. The collected audio from interviews was later transcribed for further analysis.

4 Key Findings

The focus group discussion explored potential drivers and barriers to implementing DPP within the social housing supply chain. The key areas of discussion were the perceived benefits of DPP, policy and incentive barriers, data and technological barriers, and market and societal barriers. All participants agreed on the perceived benefits of implementing DPP in the construction industry and social housing, mainly increased availability and traceability of lifecycle information across different stages of construction and building development. They emphasised the direct benefits of DPP, including improved decision-making regarding material use, replacement of building parts, and maintenance efficiency. Furthermore, they placed importance on customer service, which is central to their organisation, and emphasised the direct, tangible benefits to tenants from DPP. One of the participants noted that "*Having clear information about the materials used in the building would improve future maintenance, and material traceability would help in making replacement decisions much easier and faster*".

Overall, participants emphasised that DPP has the potential to support circular economy practices, such as enabling the tracking and reuse of materials in refurbishment, further supporting sustainable construction practices.

Policy and regulatory barriers were identified as key influences for stakeholders regarding the implementation of DPP in the Scottish Social Housing sector. The participants shared a collective view on the need for a stronger, clearer policy direction for DPP adoption in the construction sector. The participants showed a concern regarding uncertainty in current legislation to support DPP implementation through statements like "*There is a requirement of stronger policy guidance before construction and social housing organisations are required to expand their investments in DPP-type initiatives*". Therefore, a strong policy backbone at the national level is required as a key driver of DPP implementation; otherwise, it is a significant barrier to its implementation. Data & technological barriers, such as incomplete lifecycle data, traceability gaps, and data standardisation gaps, were considered by the participants to be of considerable importance to DPP implementation. Whereas data inaccuracies, limited integration of BIM/LCA tools, and limited integration of economic factors in tools were considered to have medium to low impacts on DPP implementation. One of the participants highlighted the complexity of managing large volumes of material data by stating that "*The actual challenge is not just the collection of material data but ensuring that it is standardised for usage in wider systems and tools*". Market and society barriers were given the least importance among all barrier categories. However, one of the most important sub-barriers, given high importance, was supply chain fragmentation, which could significantly influence DPP implementation. The participants highlighted that contractors and suppliers may not have the capacity to meet the data needs of DPP. A participant stated that "*The supply chain needs to adapt significantly, and smaller suppliers may be unable to provide sufficient or good quality material data*".

The personal interviews with the stakeholder from the Procurement team emphasised policy and regulatory support as the backbone of the DPP implementation, stating that "*the approach feels very abstract because there needs to be legislation and policy-driven enforcement is likely necessary*". Further, they emphasised that there are inconsistent approaches among suppliers, which might create a significant barrier to meeting

DPP data requirements. The second interview with the stakeholder from the New Build team emphasised the need to integrate DPP into current digital construction systems for effective implementation, stating that "*DPP would need to integrate with the current systems; otherwise, it would just become another layer of data management*". The third interview with the stakeholder from the Finance team emphasised that the organisation would need robust business cases and evidence of investment returns from approaches such as DPP before committing to wider implementation.

5 Conclusions and Implications for DPP Implementation

This research study investigated the potential drivers and barriers to implementing DPP in social housing. The focus group and personal interview findings indicate that policy and regulation barriers will be the most significant challenges for DPP adoption in Scotland. At the same time, the results highlight significant benefits from DPP, including increased material traceability, supply chain transparency, and better asset management in social housing. Overall, the results indicate that the successful implementation of DPP requires strong legislation, data standardisation, and supply chain collaboration. The study warrants future research into practical implementation frameworks and data requirements for DPP adoption for social housing in Scotland.

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Using AI Models in Life Cycle Inventory Analysis to Support Product Ecodesign Practices

Andréa Franco Pereira(✉), Arthur Filipe Neves Silva, and Leonardo Oliveira

Universidade Federal de Minas Gerais, Belo Horizonte, Brazil
andreafranco@ufmg.br

Abstract. Project support systems are constantly incorporating advances in information technology, and currently, Artificial Intelligence (AI) is part of the evolution of these systems. Concerning product design, the main applicable AI categories are machine learning, neural networks, computer-aided visualization systems, and natural language processing systems (such as Large Language Model - LLM). The objective of this study has been to understand how to use AI to assist the practice of ecodesign through Life Cycle Assessment (LCA), especially the Inventory Analysis phase. Studies are very recent on the application of AI into the LCA method. In this work, the proposed methodology has had an exploratory approach, seeking (1) to analyze the literature on studies incorporating AI into the LCA method; (2) to understand the AI categories applicable to Life Cycle Inventory Analysis (LCIA); (3) to identify AI models to propose their application; and (4) to conduct application testing. In attempts to integrate AI into LCA, it has been observed that the most frequently used categories have been machine learning and neural networks, especially for predicting environmental impacts, based on previous LCA studies. In addition to these, LLMs have proved to be interesting in assisting the arduous task of LCI. Thus, the aim of this study is the application of an LLM to a light shelf project, in which the LCA had already been performed by the team, in order to compare the performance of applying such LLM, with a view to analyzing its potential use in other projects. The application has proved promising, assisting designers in the practice of LCIA phase and for decision-making.

Keywords: Artificial Intelligence · AI · Life Cycle Assessment · LCA · Life Cycle Inventory Analysis · LCIA · Ecodesign · light shelf

1 Introduction

Research on design-aid systems and artificial intelligence (AI) is not new; some of it dates back over 60 years. All the technological advances arising from these areas have significantly impacted the way we develop projects. The personal computer, CAD (Computer Aided Design), NURBS (Non-Uniform Rational Basis Spline) surfaces, and BIM (Building Information Modeling) are some examples. However, the use of AI-supported systems has currently gained prominence.

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Design-aid systems have historically incorporated advances in information technology and algorithms focused on, for example, 3D modeling, dimensional databases, or CNC (Computer Numeric Control). Today, embedded AI modules are a definitive part of the evolution of these applications, which is dedicated to performing a single task in an extremely efficient and valid manner (Mielke, 2021).

Scott and Shaw (2023) define AI as a broad category of technologies whose goal is to automate tasks by mimicking human behavior. These adjacent technologies are experiencing rapid growth in applicability. The main categories, or drivers of AI development, include: a) machine learning, b) neural networks, c) computerized visualization systems, and d) natural language processing systems. Table 1 briefly describes these development categories.

Table 1. Artificial intelligence research typology (Gomes, Pereira, 2023).

Name	Description
Machine Learning (ML)	Training and algorithms to learn from data and make predictions or decisions without being programmed. Examples: recommendation algorithms, fraud detection, and image recognition.
Neural Networks	AI models inspired by the structure and function of the human brain, used in image recognition and natural language tasks.
Generative Adversarial Networks (GANs)	A subset of Neural Networks, where two networks compete against each other. Examples: generating images, creating deepfakes, and generative systems for AECD.
Deep Learning (DL)	A subset of Machine Learning, to process and analyze complex data. Examples: autonomous vehicles, language translation, among others.
Natural Language Processing (NLP)	AI model focused on understanding and generating human language. Examples: customer service chatbots, generative chatbots from text, virtual assistants Siri or Alexa, and language translation tools.
Speech Recognition	AI that converts spoken language into written text. Examples: voice assistants, voice controls, and speech-to-text transcription.
Computer Vision	AI model that understands and interprets visual information from images or videos. Examples: Facial recognition, object detection, and autonomous vehicle perception systems
Expert Systems	AI models that mimic human expertise in a specific domain, using knowledge and rules to make recommendations or decisions. Examples: Medical diagnostic systems, financial planning systems, AECD creation aids, and customer support chatbots.
Robotics AI	AI models used in robotics, enabling environmental recognition, decision-making, and the execution of physical tasks. Examples: Autonomous robots, drones, and industrial robotic assistants.

(*continued*)

Table 1. (*continued*)

Name	Description
Generative AI	AI models capable of generating text, images, or other media in response to requests in plain language.
Reinforcement Learning	AI models that train an agent to make decisions in an environment, with feedback in the form of rewards or penalties. Examples: Games, autonomous robots, and optimization algorithms.

Concerning product design, the main applicable AI categories are machine learning, neural networks, computer-aided visualization systems, and natural language processing systems (such as Large Language Modeling - LLM).

As part of product design, this study focuses on ecodesign, with the objective of understanding how to use AI to assist the practice of ecodesign through Life Cycle Assessment (LCA), especially the Inventory Analysis phase. The aim is the application of an AI model, such as LLM, to a light shelf project, in which the LCA had already been performed by the team, in order to compare the performance of applying such LLM, with a view to analyzing its potential use in other projects.

2 Literature Review

2.1 Studies Incorporating AI into the LCA Method

LCA is a method defined by the ISO 14040 series of standards (ISO, 2006), which evaluates the environmental impacts of a given product's life cycle, from the extraction of its raw materials to its disposal or reuse through recycling or energy conversion processes. It consists of four phases: 1. Objective and Scope: defining the purpose of the study and the limits of the system to be modeled; 2. Inventory Analysis: identifying the processes involved in the system and collecting quantitative input and output data; 3. Impact Analysis: categorizing and evaluating potential environmental impacts based on the results of the inventory analysis; 4. Interpretation: understanding the modeling and analyzing the results for decision-making. Although recognized as a useful method for quantitative analysis of various categories of impact, LCA continues to be considered a costly method in terms of knowledge and time, especially in the Life Cycle Inventory (LCI) Analysis phase, which is estimated to account for 70% to 80% of the time and costs of an LCA study (Popowicz et al., 2025).

In light of this, over the past five years, several studies have been conducted with the aim of integrating AI into LCA practice. Some articles present literature reviews, showing the increase in research seeking this integration, such as Cerchione et al., 2025; Popowicz et al., 2025; Gachkar et al., 2024; Martinez-Ramon et al., 2024.

It is possible to observe a search for the combination of mathematical models, statistical methods, and AI models to predict potential environmental impacts. Koyamparambath et al. (2022) have tried to use data from environmental product declarations (EPDs) of construction products to predict the environmental performance of a product. Jesus, Oliveira-Esquerre, Medeiros (2022) have studied AI models to predict impacts on

industrial water treatment. Martinez-Ramon et al. (2024) have proposed frameworks for the application of machine learning enabling predictions of LCIs or LCA performance indicators. Ibn-Mohammed et al. (2023) have explored machine learning frameworks for improved predictions of impacts of functional materials and devices. They suggest that "deep learning (DL) approaches like convolutional neural networks (CNN) can be used to automatically develop a bill of quantity of materials from images, diagrams, or maps to serve as input data for LCA". Mohammadi-Kashka et al. (2023) compared AI models for predicting energy use, employing neural networks and ANFIS (Adaptive Neuro-Fuzzy Inference System) – a hybrid system that combines fuzzy logic and artificial neural networks.

Such research is still in its early stages and seeks to predict the environmental impacts caused by products using methods that require extensive specialized knowledge in computer science. However, currently, in the practice of LCA application, the impact analysis phase is not a major problem, since it is done using LCI databases, software and methods that are recognized and accepted. For this reason, this study seeks to explore the use of AI to facilitate the costliest phase, which, as mentioned, concerns the LCI Analysis.

In this sense, Natural Language Processing (NLP), such as Large Language Modeling (LLM), appears to be a more effective alternative. According to Ibn-Mohammed et al. (2023), these "techniques can be used to automatically extract relevant data from text-based websites sources, such as scientific literature, reports, or NLP web scraping algorithms can be utilized to perform tasks such as text mining, entity recognition, and sentiment analysis to extract data related to the inventory of a product or process, including raw material inputs, energy consumption generation emissions estimates, and waste". MacMaster and Sinistore (2024) have investigated the ability of LLMs to automate Data Quality Assessment, and the model demonstrated a high ability to mimic human reasoning. Tu et al. (2024) draw attention to the multimodal capabilities of LLMs. They possess reasoning capable of performing semantic searches and inferring processes through multidisciplinary knowledge acquired during training.

The integration of customized LLMs into LCA allows researchers, even without in-depth training, to find qualitative solutions and technical guidance (Chen et al. 2024).

2.2 AI Categories Applicable to Life Cycle Inventory Analysis

Preuss, Alshehri and You (2024) indicate that LLMs hold significant promise for developing a LCI and summarizing and communicating LCA results. Although, "challenges arise from the inclusion of hallucinations in the content generated by the LLM, which can be mitigated if the LCA practitioner uses prompt engineering techniques". Furthermore, according to the authors, when integrated with multi-modal LLMs, vision-based tasks (images and video) can be performed, which can aid in the dissemination of LCA results.

A study has been done using three state-of-the-art LLMs, including Google Gemini, Gemini Advanced, and GPT-4 (Preuss, Alshehri, You, 2024). They have considered a LCA scenario where focuses on potential choices for land use change with tradeoffs between food and energy production. It has been asked to respond to: Prompt 1: "The following is an example scenario for a life cycle assessment. What is an appropriate goal and scope definition for this scenario? Please justify your choices"; Prompt 2: "what

would be an appropriate functional unit for the LCA in this scenario?"; and Prompt 3: "Should I use ReCiPe 2016 or CML as a life cycle assessment methodology?".

For the present study, only the first of these three prompts will be relevant. Therefore, Table 2 shows some conclusions reached by the authors.

Table 2. Responses' discussion. (Preuss, Alshehri, You, 2024).

LLMs	Prompt 1
Gemini	Gemini is able to understand some of the contents of a goal and scope definition, but also included extraneous. It's ability to identify a goal, LCA type, functional unit, and system boundaries are adequate, but could significantly benefit from further refinement. The system boundaries are vague, but a geographic boundary was given with an appropriate justification.
Gemini Advanced	Gemini Advanced provides a specific goal, system boundary, and functional unit. Provides an adequate system boundary. The functional unit provides is suitable, but needs verification from an LCA practitioner before being used as the basis of an LCA.
GPT-4	GPT-4 provides a detailed discussion for the goal and scope definition of the scenario. A specific goal and functional unit are specified and justified, while the system boundary does not mention which stages of the product life cycle the LCA covers. While the LLM recognizes that the functional unit should enable a fair comparison between the systems, it chooses different functional units for different pathways.

3 Method

LLMs have proved to be interesting in assisting the arduous task of LCIA. In this work, its application has been based on the study of Preuss, Alshehri, and You (2024). Therefore, its application to a light shelf project, designed by the team, has been proposed, in which the LCA had already been accomplished previously. The aim is to compare the performance of LLMs results with the LCI analysis already carried out.

Two LLMs have been used for this study: (i) Gemini 3, a multimodal generative AI chatbot and virtual assistant developed by Google, and (ii) DeepSeek, an AI chatbot developed by a Chinese AI research lab. The data and the AI architecture for Gemini are based on Deep Multimodal Reasoning, an Agent-oriented approach, and Native Multimodal model, and for DeepSeek, they are based on a Mixture of Experts, a Hybrid Attention architecture, and Manifold-constrained Hyper-connections.

3.1 Object of Study: LCIA of a Light Shelf

The concept of the light shelf present in this study (Pereira, 2019) can summarize as: to reduce the consumption of electric light controlling lighting and diffusion of natural light

in a built space; target audience: architects who seek to meet the needs of environmental comfort in buildings; search for commercial products; commercial standardization, modularity, ease of installation, use and maintenance; modularity for internal and external use; static use, providing easy cleaning; curve for better reflection of light; simple fittings; use of recycled aluminum in foundry process and profiles available in the market; finishing for better light reflection on top; valorization of recycled aluminum. The product presents four modules of different dimensions for better adaptation to the façade orientations.

The LCI (see Fig. 1) has been modeled in GaBi 6.0 LCA software using its process database. It is defined as: the light shelf is composed of two sinuous side pieces, similar to a French hand for attachment to the wall. In these parts, longitudinal round rebars are fixed in which flat plate sheets accompany this longitudinal line. It is expected that the manufacture of this light shelf will be done at Belo Horizonte, Minas Gerais, Brazil and will use of recycled aluminum cast in the side parts, round rebar and aluminum plates available on the market for the other components. The function of the product concerns the reflection of natural light in opening windows corresponding to a length of 1500 mm. The functional unit is therefore established by the reflection surface of 1.3m^2, defined by the dimensions of 865 x 1500 mm of the module considered standard in the design. The quantitative data has been defined as follows: 6 parts of 19 mm rebar = 6.976 kg, 5 parts of 1.5 mm sheet = 9.518 kg and 2 side parts by casted aluminum = 6.005 kg.

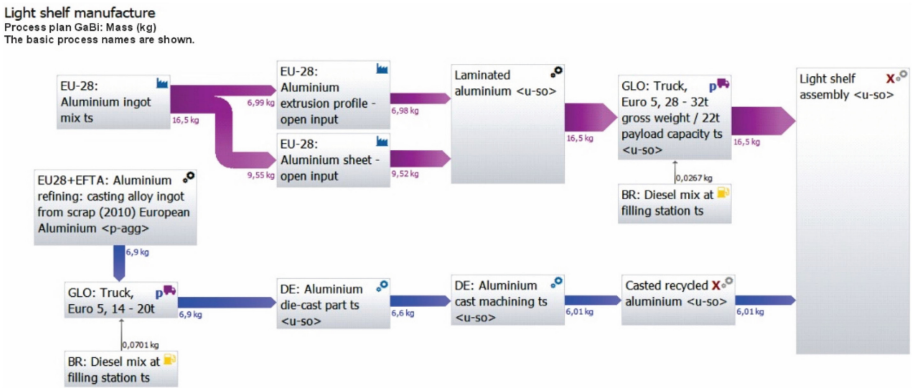


Fig. 1. LCI of the Light shelf - aluminum and side parts from recycled aluminum (Pereira, 2019).

3.2 Testing LLMs to LCI Analysis of the Light Shelf

For the LCI Analysis, four questions have been defined for LLMs application:

Prompt 1: "The following is an example scenario for a life cycle assessment. What is an appropriate goal and scope definition for this scenario? Justify your choices."
Prompt 2: "What industrial processes are involved in this scenario?"
Prompt 3: "How far from Belo Horizonte, Brazil, will I find the processed materials needed to assemble the light shelve at Belo Horizonte?"

Prompt 4: “What is the best visual representation of the production system in this scenario? Do not forget the distances involved in the process.”

In Gemini 3, all questions have been asked using the “reasoning” tool and in DeepSeek, it has been asked using the “deep thinking” tool. Furthermore, the questions have been asked in both English and Portuguese. In general, DeepSeek provided more detailed and in-depth answers compared to Gemini 3. Apparently, Gemini 3’s answers have been based on the reference article published by the team (Pereira, 2019). Despite this, the answers to Prompts 1 and 2 have been correct and relatively similar in both LLMs.

For Prompt 3, the DeepSeek responses have been much more accurate and detailed, including specific supplier names. However, the question in Portuguese generated more accuracy regarding the raw material production locations than the question asked in English. For Prompt 4, the diagram produced by Gemini 3 proved to be more illustrative and communicative (see Fig. 2), while the DeepSeek diagram has been more technical, corresponding better to the usual LCA diagrams.

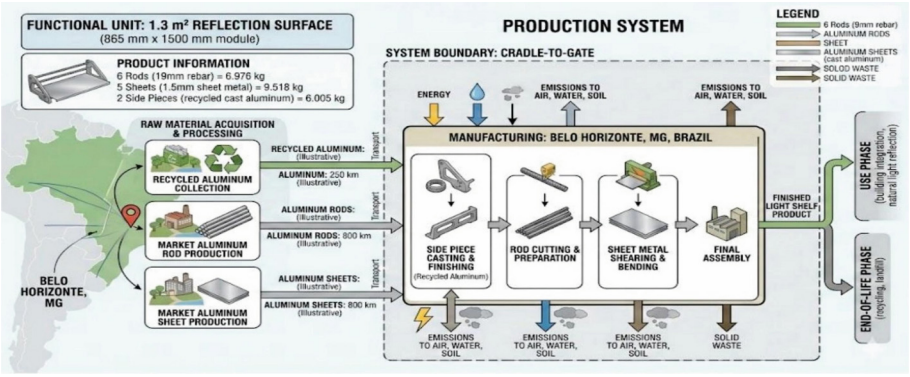


Fig. 2. Diagram produced by Gemini 3 - more illustrative and communicative

4 Conclusion

This study has sought to understand how to use AI to assist the practice of ecodesign through LCA, especially the LCI Analysis phase. For this, it has been proposed the application of two LLMs, Gemini 3 and DeepSeek, to a light shelf project, in which the LCA had already been performed by the team, in order to compare the performance of applying such LLMs. The results showed that the application of LLMs is promising for facilitating the task of inventorying the processes involved and visualizing the product system under analysis. To this, the question in Prompt 3 appears to be the most important, and should be well-developed as precise as possible based on the design specifications. The answer generated in this question will be fundamental for a better representation of the diagram. Prompt 1 and 2 have proved to be preparatory and perhaps unnecessary. In this initial exploratory study, a simple product involving few processes has taken as the

object of analysis. The continuation of the research foresees the application of LLMs to a more complex product.

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