

Developing a three-level circular economy framework to measure circularity for meso-level assessment in pavement construction[☆]

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HIGHLIGHTS

- Meso-Level circularity framework with three-level: 6 indicators, 17 standards and 44 factors.
- This study applied SF-AHP for meso-level circularity index assessment.
- CE system design is the most influential circularity indicator in the framework.
- CE system design and technical indicators have the weakest implementation scores.
- Meso-Level circularity index is 56.9 %, indicating moderate pavement circularity.

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ABSTRACT

The transport sector significantly contributes to global resource consumption and CO₂ emissions, with pavement construction playing a key role. While circular economy principles have been adopted, existing research primarily addresses macro-level policies and micro-level implementations, leaving meso-level assessment under-explored. Establishing an industry-accepted circular economy system for pavement construction is fundamental for improving the overall circularity index and integrating these principles across all dimensions. This study develops a three-level conceptual model to systematically measure circularity in the pavement construction sector. The model is based on an extensive literature review, standards analysis, and discussions with expert panels. Utilizing the spherical fuzzy analytic hierarchy process framework, this approach is applied for the first time in the pavement construction sector to reduce uncertainty and bias. Moreover, the study synthesizes feedback from 11 key stakeholders, including pavement construction companies, consulting firms, and academic experts from multiple countries, to assess the meso-level circularity index. The results reveal a circularity index of 56.9 %, indicating moderate integration of circular economy practices within the industry and highlighting critical areas for improvement. Additionally, the social indicator, despite having a relatively low weight, demonstrates high implementation potential, suggesting that prioritizing it through policy interventions could lead to short-term gains. The meso-level evaluation model bridges the gap between macro-level policies and micro-level implementation, providing decision-makers and companies with actionable insights into the industry's sustainability status. Furthermore, the proposed model integrated with spherical fuzzy analytical hierarchy process offers a valuable reference framework for promoting circular economy practices in other industries.

1. Introduction

Transport plays an essential role in economic development across the globe. However, the construction and maintenance of transport infrastructure lead to significant environmental impacts and resource consumption. Between 2015 and 2022, the transport sector's fossil fuel

consumption contributed to 200 million metric tons of CO₂ emissions (IEA, 2023). Notably, emissions associated with the entire lifecycle of pavement contribute to 5 %–25 % of the total CO₂ emissions from the transport sector (Liu, N. et al., 2022). In addition, pavement construction demands vast quantities of natural resources. In 2023, among the reported 241 million metric tons of construction sand and gravel used in

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the United States, approximately 106 million metric tons (44.1 %) were designated for pavement construction (USGS, 2025). Despite these challenges, pavement construction remains a critical infrastructure for all countries, highlighting the pressing need to address its associated environmental and resource concerns.

Circular economy (CE), as a “cradle-to-cradle” model, has gained significant attention in recent years as a sustainable alternative to the traditional linear economic model of take-make-dispose (Reuter et al., 2019). It aims to eliminate waste, circulate materials at their highest value, and regenerate natural systems throughout the lifecycle of products (EMF, 2021). By shifting the focus from resource extraction, use and disposal to material reuse and recovery, CE provides a promising framework to address the challenges of environmental impacts and resource consumption posed by the pavement construction sector (Martin et al., 2024). Compared to traditional recycling processes, CE emphasizes designing waste recovery and reuse pathways from the outset, aligning with global sustainability goals such as the United Nations Sustainable Development Goals, particularly Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action) (UN, 2023). Promoting the circular economy is therefore a critical component of transitioning to low-carbon and sustainable development.

To facilitate the adoption and to evaluate the effectiveness of circular economy practices, researchers have introduced the concept of circularity index. Through dimensional indicators that represent the economic, social, and environmental aspects of specific industries and regions, the circularity index evaluates the state of circularity (Ness et al., 2007). By assigning different weights to these indicators, the index provides a comprehensive and quantified evaluation, reflecting the overall performance of circular economy practices (Muñoz et al., 2024). Following the three-level classification proposed by Ghisellini et al. (2016), circular economy research can be analyzed at the micro-, meso-, and macro-levels. In the classical formulation, micro-level studies focus on individual companies or products, meso-level studies address eco-industrial parks and industrial symbiosis districts and networks, and macro-level studies consider cities, regions and nations. In subsequent applications, particularly in studies of industrial and infrastructure systems, the meso-level has also been interpreted more broadly to cover sectoral value chains that sit between individual firms and territorial systems. This broader interpretation is consistent with industrial ecology, which distinguishes facility, inter-firm, regional and global levels of analysis, and with industrial symbiosis, which primarily concerns exchanges of materials, energy and by-products between organizations (Chertow, 2000; Zhu et al., 2007). On this basis, this study takes the pavement construction sector as the unit of analysis and examines how circular economy practices govern the flows of materials, energy and reclaimed products along its value chain, and is therefore classified as meso-level.

In the pavement construction sector, the adoption of the circular economy is progressing yet the development of the circularity index is nascent, with current advancements primarily concentrated at the macro- and micro-levels (Liu, Z. and Kringos, 2024). At the macro-level, the circularity index is often applied to analyze regional or national initiatives or pavement management systems, integrating policy impacts, economic factors, and environmental outcomes (Commission, 2020). For instance, Wasiq and Golroo (2024) applied the Analytic Hierarchy Process (AHP) to evaluate the circularity index of pavement management system constructing a composite value from environmental, financial, and quality perspectives and applying it to country-level datasets for several European pavement management systems. At the micro-level, researchers have widely applied methods such as life cycle assessment, material circularity indicator, and life cycle cost analysis to evaluate the circularity index of recycled pavement, including asphalt pavements made from recycled materials (Bautista Carrera, 2022), reclaimed asphalt pavements (Mantalovas and Di Mino, 2019), and identify optimizing opportunities across different stages of the pavement lifecycle (Ibrahim et al., 2024). Despite these

advancements, meso-level applications of circularity index in the pavement construction sector remain underexplored (Liu, Z. and Kringos, 2024).

In contrast, the meso-level serves as an intermediary that connects policy objectives with on-site practices by targeting sectoral operations and sector-specific coordination mechanisms (Bahramianrood et al., 2024). For example, CE standards such as BS 8001:2017 reflect meso-level strategies that translate policy goals into sector-specific practices through system-level guidance (Pauliuk, 2018). However, such practices in the pavement construction sector remain fragmented or absent. Without this integration, macro policies may lack pathways for implementation, and micro innovations may fail to scale up. Bridging this gap requires a dedicated evaluation framework tailored to the characteristics of the pavement construction sector, enabling consistent feedback from implementation to policymaking (Liu, Z. and Kringos, 2024).

This study focuses on the meso-level practice in the pavement construction sector. The sector is defined to include all stages of the pavement lifecycle, from circular economy system design and material planning to extraction, production, mixing, transport, pavement construction, maintenance, and end-of-life waste management and recycling. This scope enables the evaluation of how industry-level strategies align macro-level policies with micro-level practices.

This paper aims to evaluate the current state of meso-level circular economy implementation in the pavement construction sector and propose a novel three-level conceptual model designed to bridge the gap between macro-level theoretical principles and micro-level practical applications. The model comprises three hierarchical levels: indicators, standards, and factors, providing a structured approach to systematically evaluate circularity. It integrates six comprehensive circularity indicators: circular economy system, material, cost, environmental, social, and technology, calculated through decision-makers (DMs) assessment to develop a meso-level circularity index. By offering enhanced granularity and addressing ambiguities between meso- and micro-level scopes, the three-level model ensures a comprehensive and actionable framework for evaluating circularity.

The paper is organized as follows: Section 2 discusses the literature review. The methodologies employed in this research will be detailed in Section 3, and the results obtained will be discussed in Section 4. Section 5 summarizes the findings and contributions of this work and provides recommendations for future research.

2. Literature review

This literature review is divided into four sections. Section 2.1 summarizes the current applications of circular economy principles in the pavement construction sector. Section 2.2 discusses the existing meso-level indicators and their relevance. Section 2.3 reviews the application of spherical fuzzy analytic hierarchy process (SF-AHP) in evaluations for complex decision making. Section 2.4 highlights the research gaps to be addressed by this study.

2.1. Current applications of circular economy in pavement construction

The adoption of CE principles in the pavement construction sector is relatively recent, driven by the pressing need to mitigate environmental impacts and optimize resource use (Pereira and Vieira, 2022). CE initiatives in this sector predominantly focus on recycling materials (Mantalovas and Di Mino, 2019; Tushar et al., 2022), reducing environmental impacts (Li et al., 2019), reducing costs (Babashamsi et al., 2016), and enhancing the lifecycle performance of pavements (Zhao and Yang, 2023). Macro-level policies, like the EU's Resource Efficiency Platform, and national frameworks in countries like the UK and France, emphasize regulatory compliance and resource efficiency (Platform, 2014; Mantalovas and Di Mino, 2019). However, macro-level, policy-driven efforts often face challenges in micro-level implementation, such

as regulatory restrictions on the use of recycled materials, which hinder broader adoption (Mantalovas et al., 2020).

At the micro-level, to achieve sustainability, recycled materials such as reclaimed asphalt pavement (Mantalovas and Di Mino, 2019), glass (Khater et al., 2021), rubber (David et al., 2018), and construction and demolition wastes (Zou et al., 2020) are increasingly being used as substitutes for traditional aggregates. Methods such as life cycle assessment (Mantalovas and Di Mino, 2019), life cycle cost analysis (Suwanto et al., 2023), and material circularity indicator (EMF, 2015b; Mantalovas and Di Mino, 2019) are employed to quantify and evaluate the circularity of pavements across environmental, cost, and material indicators. While these efforts lay the foundation for CE practices, there remains a gap in meso-level integration that connects policy objectives with practical outcomes.

2.2. Current research on meso-level circular economy indicators

The transition toward a circular economy in the pavement construction sector remains slow, primarily due to the absence of meso-level indicators to evaluate sector-wide performance and enable consistent performance assessment and stakeholder coordination (Liu, Z. and Kringos, 2024). Mantalovas et al. (2020) surveyed national road authorities across nine European countries and found that while CE principles are acknowledged, their implementation is fragmented and often limited to material substitution or asphalt recycling, with no strategic roadmaps or indicators (Mantalovas et al., 2020). This highlights an urgent need for a sector-specific framework that can operationalize circularity beyond isolated practices. Although significant differences exist across sectors in the production and manufacturing process, existing studies and standards can serve as valuable references for designing a comprehensive and sector-specific framework tailored to the pavement construction sector. Table 1 summarizes the indicators covered across key studies and international standards, highlighting their scope and limitations.

Based on the current practice of circular economy in European pavement construction, Mantalovas et al. (2020) concluded that circular design is a crucial component for achieving sustainability. This conclusion is consistent with the principles found in standards (BSI, 2017; EN, 2022; ISO, 2024). Beyond circular design, indicators like material circularity, environmental performance, economic performance, social impact, and technical aspects are consistently included in most circular economy standards and studies. These indicators have been widely applied in meso-level assessment models across sectors such as supply chain management (Shete et al., 2020), manufacturing (Vimal et al., 2021), and construction (Abadi et al., 2021), underscoring their fundamental importance in evaluating circular economy practices. Most CE indicators align with the three pillars of sustainability: environmental, economic, and social (Heshmati, 2017). In addition, many

studies group indicators according to CE principles, with different sectors developing indicator sets suited to their specific boundaries and operational characteristics (Kristensen and Mosgaard, 2020). As such, Table 1 does not claim to be exhaustive, but offers a representative synthesis of current meso-level indicator practices relevant to circularity assessment.

Piñones et al. (2023) proposed a meso-level framework for urban infrastructure projects under the Circular Economy 4.0 concept. However, the framework's reliance on input from a single stakeholder group comes with significant limitations. Due to varying levels of expertise among stakeholders, this approach risks potential biases that may compromise the accuracy of the results. Furthermore, this reliance limits the integration of critical environmental and technical dimensions, reducing the comprehensiveness of the evaluation process. Although the framework was designed for meso-level applications, its implementation in evaluating three specific pavement projects further blurs the distinction between meso- and micro-level definitions. These limitations underscore the need for a more inclusive and multi-dimensional framework tailored to the specific requirements of the pavement construction sector.

2.3. Application of spherical fuzzy analytic hierarchy process in circular economy

Multi-criteria decision-making (MCDM) plays a crucial role in evaluating CE strategies at the meso-level (Žak et al., 2014; El Alaoui, 2020). The SF-AHP is particularly effective in addressing uncertainty by incorporating membership, non-membership, and hesitancy values. This feature enhances the robustness and reliability of evaluations involving expert inputs and conflicting criteria (Kutlu Gündoğdu and Kahraman, 2020).

In circular economy applications, SF-AHP has demonstrated success across various contexts. Alimohammadlou and Khoshsepehr (2023) applied SF-AHP in a two-level framework addressing governmental, economic, social, environmental, and technological dimensions within the broader context of Social 5.0 and sustainable development, effectively managing sustainable development challenges. Similarly, Unal and Temur (2022) utilized SF-AHP to optimize sustainable supplier selection in the logistics sector. These studies highlighted the adaptability of SF-AHP in tackling complex decision-making processes within circular economy contexts.

Despite its demonstrated effectiveness, the application of SF-AHP in the pavement construction sector remains underexplored. This study addresses this gap by employing a method to evaluate the meso-level circularity index. By integrating inputs from DMs across multiple countries and stakeholders, the evaluation framework achieves greater precision, comprehensiveness, and applicability.

Table 1
Summary of circular economy indicators across studies and standards.

Indicator	ISO (2024)	EN (2022)	BSI (2017)	De Pascale et al. (2021)	Abadi et al. (2021)	Pauliuk (2018)	Vimal et al. (2021)	Shete et al. (2020)	Piñones et al. (2023)
Material Circularity	✓	✓	✓	✓	✓	✓	✓	—	✓
Environmental Performance	✓	✓	✓	✓	✓	✓	✓	—	—
Economic Performance	—	✓	✓	✓	—	✓	✓	✓	✓
Social Impact	—	✓	✓	✓	✓	✓	✓	✓	✓
Technical	—	—	✓	—	✓	✓	—	✓	—
Lifecycle Resource Efficiency	—	—	—	—	✓	✓	—	—	—
Management and Policy	—	—	✓	—	—	—	✓	✓	—
Circular Design	✓	✓	✓	—	✓	—	—	—	✓
Circular Operation	—	✓	—	—	✓	—	—	—	✓
Deconstruction and Resource	✓	—	—	—	—	—	—	—	✓
Stock and Sufficiency	—	—	—	—	—	✓	—	—	—

2.4. Research gaps and contribution of the work

As reviewed in Section 2.1 to 2.3, the pavement construction sector lacks a meso-level conceptual model to evaluate the implementation of macro-level policies at the micro-level. This absence creates a significant gap in connecting policy objectives with practical applications, leaving the sector without a comprehensive framework for assessing CE practices. Existing studies often conflate meso- and micro-level definitions,

further complicating the development of robust evaluation models. Moreover, many rely on single stakeholder inputs, resulting in limited perspectives and insufficient integration of technical and environmental dimensions.

This study addresses these gaps by proposing a tailored three-level conceptual model specifically designed for the pavement construction sector. The model was developed through a rigorous process comprising an extensive literature review and standards analysis to ensure

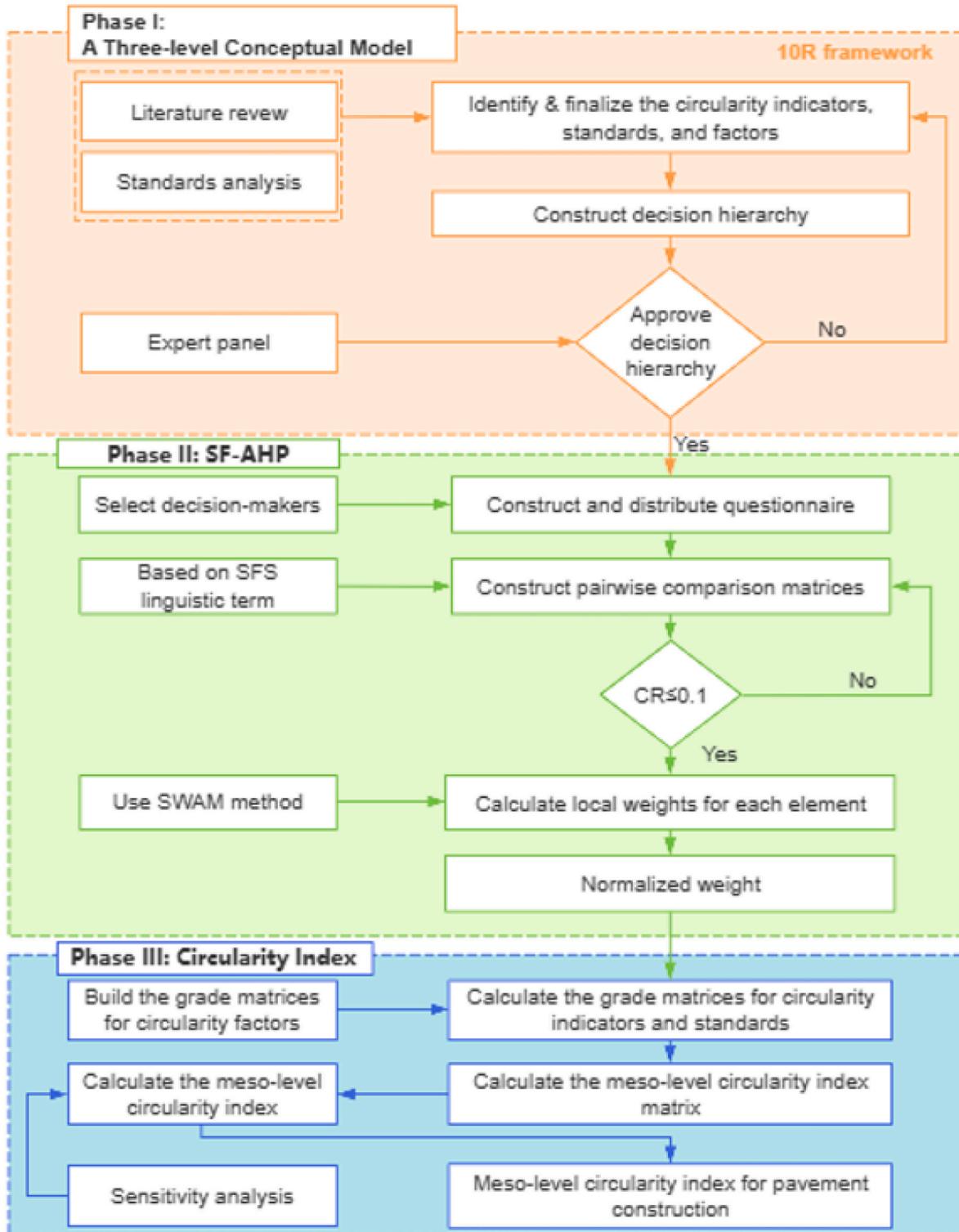


Fig. 1. Proposed framework for calculating the meso-level circularity index.

alignment with internationally recognized CE frameworks, and expert panels to validate the relevance and applicability of selected indicators. By integrating inputs from diverse stakeholders across the UK, China, and European Union countries, the framework employs the SF-AHP to facilitate robust, multi-dimensional evaluation. This framework introduces a circularity index to evaluate the meso-level implementation of CE principles in pavement construction, encompassing six critical dimensions. This innovative model bridges macro-level policy goals with practical implementation, offering a comprehensive tool to advance CE practices in the pavement construction sector.

While this study identifies six core circularity indicators, they represent overarching categories within a structured three-level evaluation framework. These are further elaborated into 17 circularity standards and 44 circularity factors, allowing a more nuanced and comprehensive assessment aligned with sector-specific needs. Some themes commonly found in other meso-level studies, such as supply chain management or cross-sector material flow, are not explicitly included due to defined research boundaries, which focus exclusively on the pavement construction sector. Although not every emerging indicator may be covered, the framework emphasizes relevance, coherence, and applicability within the pavement sector context. Section 3 provides a full explanation of the framework design and decomposition logic.

3. Methods

This section introduces a meso-level assessment framework for the pavement construction sector, developed to evaluate the circularity index based on responses from DMs. The methodology of this project is divided into three distinct phases. Fig. 1 presents the overall framework of the methodology and elaborates on the connections between each of the phases.

Phase I: A three-level conceptual model, encompassing circularity indicators (CIs), circularity standards (CSs), and circularity factors (CFs), was developed through an extensive literature review, analysis of relevant standards, and incorporation of expert feedback to ensure its applicability to the pavement construction sector.

Phase II: The SF-AHP method, using the spherical weighted arithmetic mean (SWAM) operator, was utilized to calculate and integrate the weights of each component across the three levels based on judgments from DMs representing different stakeholders.

Phase III: The grade matrix provided by DMs for each circularity factor was combined with the corresponding weights to calculate the meso-level circularity index for pavement construction.

3.1. Construct conceptual model

To comprehensively incorporate all relevant meso-level indicators, standards, and factors specific to the pavement construction sector, the conceptual model was developed using a structured approach guided by the 10R framework (Refuse, Reduce, Resell, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover, Remine) (Reike et al., 2018). The 10R framework is used as a conceptual lens to guide the three-level conceptual model for pavement construction. When the framework is translated into this sector specific context, some strategies such as repair, refurbish, remanufacture, and remine are not labelled explicitly, but are embedded in factors describing pavement maintenance, rehabilitation and next lifecycle design. Circular economy design across multiple lifecycles inherently assumes repeated use and performance improvement of recycled materials, which reduces the need to remine virgin aggregates and can lower the frequency and intensity of remanufacturing interventions. These are mainly captured within the circular economy system design (I_1), material (I_2), environmental (I_4), and technical (I_6) indicators. Resell and repurpose strategies are mainly associated with the end-of-life phase of pavement assets. In the model, they are captured within the circular economy system design indicator (I_1) and the cost indicator (I_3) through factors that describe the recovery

of end-of-life pavement materials and their use either in subsequent pavement lifecycles or in other product lifecycles.

In the process of identifying circularity indicators, a comprehensive literature review was conducted, referencing meso-level CE frameworks from other industries (Govindan and Hasanagic, 2018; Vimal et al., 2021; Piñones et al., 2023; Martin et al., 2024), alongside circular economy policies issued by various nations and organizations (EMF, 2015a; EEA, 2016; Commission, 2020), existing standards (ISO, I., 2006; BSI, 2017; EN, 2022; ISO, 2024), and CE strategies adopted by pavement construction companies (Atkins, 2019; Highways, 2021; Eurovia, 2023). This process identified six key circularity indicators considered essential for assessing meso-level circularity in the pavement construction sector, namely: circular economy system design, material indicator, cost indicator, environmental indicator, social indicator, and technical indicator.

These six indicators function as a cohesive framework for assessing meso-level circularity within the pavement construction sector. Among them, circular economy system design provides the foundational context. It defines whether circularity is embedded at the design stage, how end-of-life pavement waste is managed, and how recycled materials and renewable energy are integrated and recovered. The remaining indicators evaluate specific implementation outcomes (Mantalovas et al., 2020).

Material circularity reflects the extent to which recycled inputs replace natural aggregate across life cycle stages. This directly affects environmental performance through reduced emissions and resource extraction, and also influences cost efficiency by lowering raw material and maintenance needs (Niero and Kalbar, 2019). Environmental and cost indicators together capture the product-level impacts of circular practices across the pavement lifecycle. Both are directly influenced by material strategies and technical solutions implemented at various stages of the pavement lifecycle (Garbarino et al., 2016). Technical feasibility plays a dual role. It determines the practical constraints of circular implementation and contributes to improved efficiency and resource utilization, thereby enhancing material recovery, reducing emissions, and improving life cycle cost-effectiveness. The social indicator reflects the perspectives of multiple stakeholders, including road users, construction companies, employees, and the broader society. It is shaped by their experiences in relation to environmental quality, cost savings, and the adaptability of applied technologies (Ghisellini et al., 2016).

These interdependencies ensure that the framework not only captures each indicator individually but also reflects the systemic interactions necessary to guide circular transitions in pavement infrastructure.

This initial step established a preliminary set of 22 circularity standards and 82 circularity factors, ensuring alignment with both theoretical frameworks and established evaluation criteria for the pavement construction sector. Following this, an iterative process was conducted, incorporating feedback from expert panels, and responses from the pilot distribution of questionnaires. The expert panel consultation took place through multiple meetings between June and August 2024, conducted both online and in-person to facilitate comprehensive discussions. The panel consisted of four experts: two scholars specializing in circular economy for pavement construction and two professionals from pavement construction consulting firms.

These experts reviewed and evaluated all proposed circularity standards and factors, helping to identify redundant or overlapping elements, consolidate relevant items, and suggest additional standards and factors that could influence circular economy development in the pavement sector. Based on the expert feedback, a pilot questionnaire was developed and distributed to four professionals specializing in circular economy practices within pavement construction companies. This trial survey focused on assessing the clarity, relevance, and structure of the questionnaire. Feedback from the pilot participants was instrumental in refining the question formats and response options, ensuring the final questionnaire was optimized for accurate data collection in

subsequent phases of the study.

These interactions facilitated adjustments to better align the model with the specific needs and realities of the pavement construction sector. As a result of these processes, the initial set was refined to a final framework consisting of 6 circularity indicators, 17 circularity standards and 44 circularity factors, which are detailed in Table 2. This streamlined structure ensures both comprehensiveness and practicality in evaluating CE performance within the sector.

The framework is organized in three levels, with circularity indicators, standards, and factors arranged in a top-down structure. At the top level, six circularity indicators define the main dimensions for assessing meso-level circularity in pavement construction. If only indicators and factors were used, the indicators would remain too abstract for decision makers, while the factors would be too numerous and fragmented. An intermediate level of circularity standards is therefore introduced to translate these high level indicators into sector specific performance requirements, consistent with three-level circularity frameworks proposed in previous studies such as Vimal et al. (2021). At this level, each standard is developed based on literature, international standards and industry practice. At the bottom level, the circularity factors unpack these standards into concrete aspects that can guide expert judgement when comparing projects. Circularity factors are not intended as directly measurable variables, but as qualitative dimensions that support structured expert evaluation. The references associated with each factor indicate their conceptual origins and rationale for inclusion. Fig. 2 provides an illustration of the conceptual model's hierarchical structure across three levels.

This study represents an exploratory phase of model development. The expert panel and pilot participants were selected to ensure technical robustness and conceptual relevance. In future stages, the sample will be broadened to include a more diverse group of stakeholders, thereby enhancing the representativeness, external validity, and applicability of the proposed framework.

3.2. Spherical fuzzy analytical hierarchy process

Given the advantages of Spherical fuzzy sets in handling MCDM problems, this study will utilize SF-AHP to mitigate the ambiguity and uncertainty often present in expert decision making, and simultaneously address the biases that arise from subjective differences among various stakeholders. This integrated method enhances the robustness and accuracy of decision-making processes by systematically incorporating diverse perspectives and complex criteria into the evaluation framework (Kahraman and Gündođdu, 2021).

Step 1: Following the methodology proposed by Kutlu Gündođdu and Kahraman (2020), pairwise comparison matrices were constructed using the linguistic terms defined in Table 3. Utilize fuzzy set theory to form pairwise comparison matrices based on the concepts established in Step 1.

Step 2: Convert the decision-makers' pairwise linguistic evaluations into the corresponding score index values to check the consistency of their evaluation. When the consistency ratio (CR) is less than 10 %, it indicates that the pairwise comparison matrix is consistent.

$$CI_C = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

where CI_C represents the consistency index, λ_{max} is the largest eigenvalue of the each pairwise comparison matrix, and n represents the size of each pairwise comparison matrix.

$$CR = CI_C / RI \tag{2}$$

where CR is the consistency ratio for each pairwise comparison matrix, and RI is the random index, determined based on n (Saaty, 1980).

Table 2
The meso-level conceptual model for pavement construction sector.

Circularity factors	Description	Reference
Circular Economy Design System (I ₁)	System Characteristic (I ₁₁)	
System Compactness/Coherence/Comprehensiveness (I ₁₁₁)	Ensuring circular economy system integrity.	(Mesa et al., 2018; Martins et al., 2022)
Intensity of Loops (I ₁₁₂)	Planning material lifecycles for circularity.	Vimal et al. (2021)
Circular Economy Design System (I₁)	Management and Measure (I₁₂)	
End-of-life Pavement Waste Management (I ₁₂₁)	Managing end-of-life waste.	Vimal et al. (2021)
Greenhouse Gases Emission Management (I ₁₂₂)	Controlling lifecycle greenhouse gas emissions.	(Scott, 2017; Suzanne et al., 2020)
Water and Land Pollution Management (I ₁₂₃)	Mitigating lifecycle water and land pollution.	Breure et al. (2018)
Circular Economy Design System (I₁)	Input for Pavement Construction (I₁₃)	
Input from Recycled Pavement/Recycled Materials (Other Industry) (I ₁₃₁)	Quantifying recycled and remanufactured material inputs in construction and maintenance stages.	ISO (2024)
Input from Recyclable Energy (I ₁₃₂)	Quantifying renewable and recovered energy used in pavement construction.	ISO (2024)
Circular Economy Design System (I₁)	Closed-loop Manufacture (I₁₄)	
The Recycling of Waste Materials during Pavement Construction (Include Water Reuse)(I ₁₄₁)	Recycling and reuse materials during construction processes for subsequent pavement lifecycles or other industries.	De Pascale et al. (2021)
End-of-life Pavement Waste Recycling (I ₁₄₂)	Recovering and recycling end-of-life waste for subsequent pavement lifecycles or other industries.	(De Pascale et al., 2021; Piñones et al., 2023)
Material Circularity Indicator (I₂)	Metrics (I₂₁)	
Non-linear Flow Index (I ₂₁₁)	Reusability of end-of-life materials.	(Pauliuk et al., 2017; Mesa et al., 2018)
Utility Factor (I ₂₁₂)	Efficiency in raw material use.	Mesa et al. (2018)
Material Circularity Indicator (I₂)	Circularity (I₂₂)	
Percentage of Components Recycled from the Pavement Construction Processes (I ₂₂₁)	Ratio of materials recycled during pavement construction.	(Pauliuk, 2018; Piñones et al., 2023)
Percentage of Components Recycled from the End-of-life the Pavement (I ₂₂₂)	Ratio of materials recycled post lifecycle.	Piñones et al. (2023)
Percentage of Components Reused to Next Life Cycle of Pavement Construction Processes (I ₂₂₃)	Percentage of recovered components that are reused in subsequent lifecycles.	Piñones et al. (2023)
Percentage of Components Reused to other Industries (I ₂₂₄)	Percentage of recovered components that are remanufactured or repurposed for use in other industries.	Piñones et al. (2023)
Cost Circularity Indicator (I₃)	Investment and Cost (I₃₁)	
Technological Investments in Recycled Pavement Construction (I ₃₁₁)	Investment to improve the application of recycled and remanufacture materials in pavement construction.	Neutzling et al. (2018)
Consulting Investments in Innovative Recycled Pavement (I ₃₁₂)	Investment in consulting services to develop higher performance recycled and remanufactured materials	Anburuvel et al. (2024)

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Table 2 (continued)

Circularity factors	Description	Reference
Circular Economy Design System (I ₁)	System Characteristic (I ₁₁)	
Investments in Physical Properties Testing of Recycled Pavement (I ₃₁₃)	for maintenance to extend pavement service life. Investment in testing pavement material performance to support the use of higher performance recycled and remanufactured mixture in construction.	Anburuvel et al. (2024)
Cost Circularity Indicator (I ₃)	Value Acquisition (I ₃₂)	
Utilize Recycled Materials/Pavement in the Whole Lifecycle of Pavement Construction (I ₃₂₁)	Economic benefits from recycled and remanufacture materials in pavement construction.	(Di Maio and Rem, 2015; Gao et al., 2017)
Waste Pavement in Other Industries (I ₃₂₂)	Economic benefits from waste reused and repurposed in other industries.	Gao et al. (2017)
Environmental Circularity Indicator (I ₄)	Greenhouse Gas Emissions (I ₄₁)	
Carbon Dioxide (I ₄₁₁)	Reducing carbon dioxide emissions.	(ISO, I., 2006; EEA, 2016)
Methane (I ₄₁₂)	Reducing methane emissions.	(ISO, I., 2006; Zhao and Yang, 2024)
Nitrous Oxide (I ₄₁₃)	Reducing nitrous oxide emissions.	(ISO, I., 2006)
Environmental Circularity Indicator (I ₄)	Ecological Resource (I ₄₂)	
Marine/River Eutrophication (I ₄₂₁)	Reducing water eutrophication.	(EMF, 2016; Vimal et al., 2021)
Soil Acidification (I ₄₂₂)	Reducing soil acidification.	(EMF, 2016; Almkokdad and Zentar, 2023)
Natural Resources/Biodiversity (I ₄₂₃)	Preserving natural resources and biodiversity.	(ISO, I., 2006; Pauliuk, 2018)
Environmental Circularity Indicator (I ₄)	Pollutants and Toxic Substances (I ₄₃)	
Volatile Organic Compounds (VOCs) (I ₄₃₁)	Reducing VOC emissions.	Mesa et al. (2018)
Particulate Matter (I ₄₃₂)	Reducing particulate matter emissions.	Mesa et al. (2018)
Toxic Chemicals (I ₄₃₃)	Reducing toxic chemicals.	(Jawahir et al., 2006; Mesa et al., 2018)
Social Indicator (I ₅)	Drivers (I ₅₁)	
Driving Experience (I ₅₁₁)	Improving driving experience.	Piñones et al. (2023)
Pavement Maintenance/Reconstruction Impact on Travel (I ₅₁₂)	Minimizing disruption to traffic.	Piñones et al. (2023)
Social Indicator (I ₅)	Companies (I ₅₂)	
Construct more Conductive to Cost-saving and Environmental Friendly Pavement (I ₅₂₁)	Evaluate the impact of promoting a circular economy on the strategic direction of pavement construction companies.	(EMF, 2015; Horbach and Rammer, 2020)
Reduce Carbon Tax Payments (I ₅₂₂)	Reducing carbon tax payments for pavement construction companies.	(Lieder and Rashid, 2016; Horbach and Rammer, 2020)
Improve Productivity (I ₅₂₃)	Enhance productivity for pavement construction companies.	Horbach and Rammer (2020)
Enhance Company Image (I ₅₂₄)	Strengthening corporate reputation.	Horbach and Rammer (2020)
Social Indicator (I ₅)	Employees (I ₅₃)	
Employees Satisfaction (I ₅₃₁)	Assessing employees' satisfaction with the application of circular economy practices.	Neutzling et al. (2018)
Quality of Work (I ₅₃₂)	Evaluating the impact of circular economy training	(Melane-Lavado et al., 2018; Shete et al., 2020)

Table 2 (continued)

Circularity factors	Description	Reference
Circular Economy Design System (I ₁)	System Characteristic (I ₁₁)	
Social Indicator (I ₅)	on employees' work quality.	
Circularity Contribution to Society (I ₅₄₁)	Contribution (I ₅₄) Supporting society benefits.	(Benoît et al., 2010; Neutzling et al., 2018)
Circular Economy of Pavement Construction Contribute to Local GDP (I ₅₄₂)	Boosting local GDP.	Vimal et al. (2021)
Technical Indicator (I ₆)	Energy Technology (I ₆₁)	
The Use of New Energy or Recycled Energy in Construction Processes (I ₆₁₁)	Applying renewable/recycled energy.	Fernández et al. (2018)
Energy-saving Technologies in the Whole Lifecycle of Pavement Construction (I ₆₁₂)	Using energy-efficient technologies.	(Fernández et al., 2018; Piñones et al., 2023)
Technical Indicator (I ₆)	Process Efficiency (I ₆₂)	
Manufacturing Efficiency (I ₆₂₁)	Improving manufacturing efficiency.	(Neutzling et al., 2018; Pauliuk, 2018)
Recycling Efficiency (I ₆₂₂)	Enhancing recycling efficiency.	Silvestre and Țircă (2019)
Material Loss in Supply Chains and Production (I ₆₂₃)	Minimizing material loss.	(Lim and Sonko, 2019; Piñones et al., 2023)

Step 3: In applying SF-AHP, the process of calculating the local weights w'_i , w'_{ij} , and w'_{ijk} for \tilde{A}_{S_i} , $\tilde{A}_{S_{ij}}$, and $\tilde{A}_{S_{ijk}}$ follows the definitions described by Kutlu Gündoğdu and Kahraman (2020) (Appendix A). DMs from different stakeholders at each level provide comparisons, which are then used to calculate the local weights using the spherical weighted arithmetic mean method, as described in Equation (3).

$$SWAM(\tilde{A}_{S_1}, \dots, \tilde{A}_{S_n}) = w_1\tilde{A}_{S_1} + w_2\tilde{A}_{S_2} + \dots + w_M\tilde{A}_{S_n}$$

$$= \left\{ \begin{array}{l} \left[1 - \prod_{m=1}^M (1 - \mu_{\tilde{A}_{S_1}}^2)^{w_m^n} \right]^{\frac{1}{2}}, \prod_{i=1}^n \vartheta_{\tilde{A}_{S_1}}^{w_m^n}, \\ \left[\prod_{m=1}^M (1 - \mu_{\tilde{A}_{S_1}}^2)^{w_m^n} - \prod_{m=1}^M (1 - \mu_{\tilde{A}_{S_1}}^2 - \pi_{\tilde{A}_{S_1}}^2)^{w_m^n} \right]^{\frac{1}{2}} \end{array} \right\} \quad (3)$$

In Equation (3), \tilde{A}_{S_i} represents a spherical fuzzy set associated with the i -th component, characterized by three parameters: $\mu_{\tilde{A}_{S_i}}$, $\vartheta_{\tilde{A}_{S_i}}$, and $\pi_{\tilde{A}_{S_i}}$. These parameters denote the degree of membership, non-membership, and hesitancy, respectively. The weight w_m^n represents the experience weight assigned to the evaluation of the m -th DM for the n -th indicator, satisfying the conditions $w_m^n \in [0, 1]$ and $\sum_{m=1}^M w_m^n = 1$. The detailed experience weights for each DM are provided in Appendix A.

Step 4: Normalize the local weights w'_i , w'_{ij} , and w'_{ijk} according to Equation (4).

$$\left\{ \begin{array}{l} w_i = \frac{w'_i}{\sum_{i=1}^m w'_i} \\ w_{ij} = \frac{w'_{ij}}{\sum_{j=1}^m w'_{ij}} \\ w_{ijk} = \frac{w'_{ijk}}{\sum_{k=1}^m w'_{ijk}} \end{array} \right. \quad (4)$$

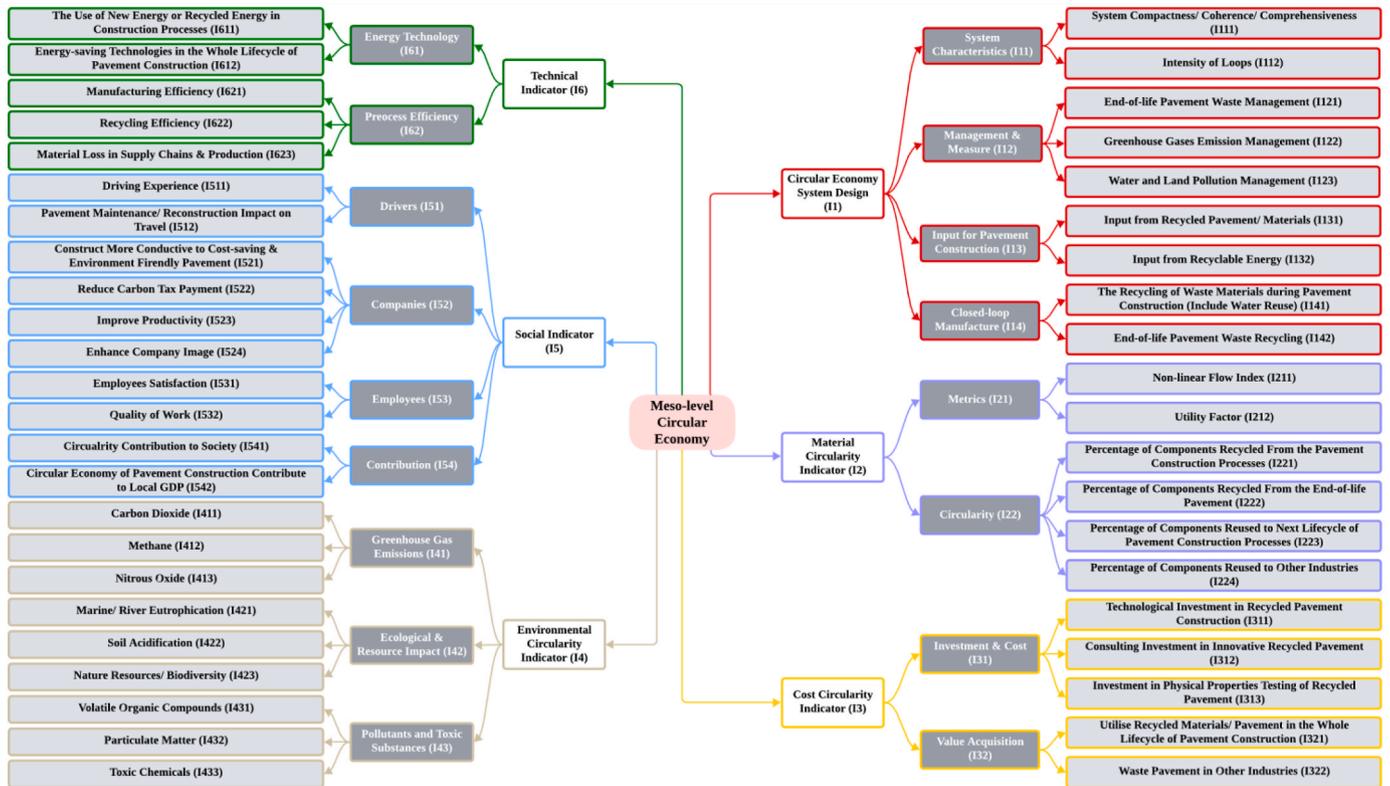


Figure 2. The conceptual model for meso-level circularity index assessment of pavement construction.

Fig. 2. The conceptual model for meso-level circularity index assessment of pavement construction.

Table 3
Spherical fuzzy sets linguistic terms (Kutlu Gündoğdu and Kahraman, 2020).

Priority in pairwise comparisons	Membership μ , non-membership θ , hesitancy π	Score Index
Absolutely low importance (ALI)	(0.1,0.9,0.0)	1/9
Very low importance (VLI)	(0.2,0.8,0.1)	1/7
Low importance (LI)	(0.3,0.7,0.2)	1/5
Slightly low importance (SLI)	(0.4,0.6,0.3)	1/3
Average importance (AI)	(0.5,0.4,0.4)	1
Slightly high importance (SHI)	(0.6,0.4,0.3)	3
High importance (HI)	(0.7,0.3,0.2)	5
Very high importance (VHI)	(0.8,0.2,0.1)	7
Absolutely high importance (AHI)	(0.9,0.1,0.0)	9

Table 4
The linguistic term for grade evaluation.

Linguistic term	Grade
Not Implemented (NI)	0
Certainly Low Implementation (CLI)	0.1
Very Low Implementation (VLI)	0.2
Low Implementation (LI)	0.3
Below Average Implementation (BAI)	0.4
Average Implementation (AI)	0.5
Above Average Implementation (AAI)	0.6
High Implementation (HI)	0.7
Very High Implementation (VHI)	0.8
Certainly High Implementation (CHI)	0.9
Fully Implemented (FI)	1.0

3.3. Calculate circularity index

Step1: DMs assessed the current application level of each circularity factor in pavement construction using the grade linguistic term in Table 4, and established the grade matrix $R_{ijk} = [DM1_{ijk}, DM2_{ijk}, \dots,$

$DMm_{ijk}]$, where $DM1_{ijk}, DM2_{ijk}, \dots, DMm_{ijk}$ represent the grades assigned by different DMs for each circularity factor.

Step 2: The weights w_{ijk} and w_{ij} obtained through Equation (4) are combined with R_{ijk} to calculate the grade matrices for circularity standards and indicators using Equation (5).

$$\begin{cases} R_{ij} = \sum_{k=1}^n w_{ijk} R_{ijk} \\ R_i = \sum_{j=1}^n w_{ij} R_{ij} \end{cases} \quad (5)$$

Step 3: The meso-level circularity index for pavement construction is calculated in Equation (6), where it is defined as the sum product of each circularity indicator's decision makers' grade matrix R_i and their corresponding weights w_i as derived from Equations (4) and (5).

$$CI = \sum_{i=1}^n w_i \times R_i \quad (6)$$

Step 4: The weighted average method was used to integrate the circularity index matrix, applying Equation (7). This approach has been widely adopted for calculating circularity index derived from the AHP method (Vimal et al., 2021).

$$\overline{CI} = \frac{1}{n} \times CI \times 100\% \quad (7)$$

Step 5: Conducted a local sensitivity analysis to measure the robustness of the model, by adjusting the weight of a specific circularity indicator w_j to w'_j , the new circularity index \overline{CI} can be expressed as in Equation (8) (Saltelli, 2008; Leonelli, 2012):

$$\overline{CI} = \left(w_j'' \times R_j + \sum_{i \neq j} w_i \times R_i \right) \times 100\% \tag{8}$$

The sensitivity coefficient *S* is calculated using Equation (9) to assess the model's sensitivity. If *S* < 1, it indicates that the selected specific circularity indicator has a minor impact on the model's sensitivity; otherwise, it exerts a significant influence on the results of the meso-level circularity index.

$$S = \frac{|\overline{CI} - \overline{CI}| / \overline{CI}}{|w_j'' - w_j| / w_j} \tag{9}$$

3.4. Data collection

Online questionnaires were distributed as the primary method for data collection, given their suitability for gathering both quantitative and qualitative insights from DMs (Kromrey, 2013). The questionnaire comprised four sections: (i) basic information of DMs; (ii) evaluations of the current application level of various circularity factors in pavement construction; (iii) pairwise comparisons of the whole conceptual model to evaluate their relative importance; and (iv) open-ended feedback and suggestions based on DMs' experiences and insights into CE development. A detailed version of the questionnaire is provided in Appendix B (Section S1).

The selection of DMs prioritized their familiarity with current CE policies and practical implementation within the pavement construction sector. Additionally, emphasis was placed on experience and their ability to provide international or cross-sectoral perspectives (Lotz et al., 2024). For DMs from pavement construction and consulting companies, the selection process focused on organizations collaborating with the Ellen MacArthur Foundation and other CE-related initiatives. Potential DMs were identified through detailed research on company websites, followed by targeted invitation emails requesting assistance in identifying suitable participants. For academic DMs, the selection was based on recent publications in leading journals (such as Web of Science Q1 journals) on the circular economy in pavement construction, ensuring alignment with the study's objectives. These DMs were contacted via email, detailed information about the project's research background, objectives, and ethical review was included in the correspondence.

The sample of DMs was drawn from pavement construction companies, consulting firms, and CE scholars located in China, the UK and European Union countries. The data collection spanned three months, from September to November 2024, resulting in 19 responses. On average, respondents spent approximately 30 min completing the questionnaire. Following a consistency ratio check, 8 responses were excluded due to logical inconsistencies or incomplete answers, leaving a final dataset of 11 valid responses. This included 3 academic experts specializing in circular economy for pavement, 3 representatives from consulting firms, and 5 from pavement construction companies. Detailed information on the DMs is summarized in Appendix B. This international and cross-sector composition was chosen to reflect diverse regulatory and market contexts, so that the meso-level framework and derived weights represent sector-wide priorities rather than the conditions of a single national system.

According to the fuzzy AHP framework, which is designed for small expert samples, the quality and consistency of expert judgements are paramount (Saaty, 1980; Kahraman and Kaya, 2010). Existing research on expert selection recommends including 2–3 DMs per stakeholder group to ensure balanced perspectives (Shete et al., 2020; Toker and Görener, 2023; Konyahoglu et al., 2024). Following this guideline, the inclusion of 11 DMs of varied business types and geographic representation is believed by authors to be reasonable and appropriate for this study.

4. Results and discussion

4.1. Spherical fuzzy analysis

Step 1: Pairwise Comparisons Since the pairwise analysis of each circularity indicator, circularity standard, and circularity factor by the 11 DMs would occupy a significant amount of space, Table 5 presents the pairwise results, spherical weights (\tilde{w}^s), and crisp weights (\bar{w}) provided by DM1 as an example.

Step 2: Consistency check The consistency of each decision maker's decision matrix was calculated according to Equations (1) and (2). The consistency test result for the decision matrices provided by DM1, as exemplified in Tables 5 and is 0.095. Since this value is less than the threshold of 0.1, it satisfies the consistency requirement.

Steps 3 and 4: Calculation of local and normalized weights The local weights w'_i , w'_{ij} , and w'_{ijk} for each circularity indicator, circularity standard, and circularity factor were calculated using the SWAM method as outlined in Equation (3). These local weights were then normalized according to Equation (4). Table 6 details the results of the aggregate and normalized weights w_i , w_{ij} , and w_{ijk} , at each level.

Based on the pairwise comparison results provided by the DMs, the calculated weights of each circularity indicator reveal that circular economy system design (I_1), environmental circularity indicator (I_4), and technical indicator (I_6) are considered the most important, with weights of 21.19 %, 18.38 %, and 16.82 %, respectively. This prioritization reflects the growing institutional emphasis on circular economy principles across countries and organizations. Designing a complete and operable circular economy system is foundational to promoting sustainability in the pavement sector, which explains why circular economy system design (I_1) received the highest importance.

Environmental performance (I_4) is increasingly emphasized due to global carbon reduction targets and the integration of environmental outcomes into company reputation and carbon taxation frameworks. The technical indicator (I_6) is strongly interconnected with material use, environmental impacts, and cost outcomes. Through innovations such as in-place recycling, energy-saving technologies and other technical improvements, pavement projects can improve lifecycle efficiency, reduce emissions, and enhance cost-effectiveness, directly benefiting stakeholders involved in pavement projects.

The cost indicator (I_3), with a moderate weight (15.34 %), captures the importance of cost-effectiveness and long-term value generation. Its comparatively lower priority may be due to limited financial incentives and a lack of a stable investment framework tailored to circular practices in the pavement sector (Mantalovas et al., 2020). However, DMs highlighted the need for targeted investment (I_{31}) in recycled pavement technologies to improve cost efficiency, showing its perceived importance for long-term gains.

Material circularity indicator (I_2) showed a similar weight pattern (15.42 %). Two key factors may explain this. First, although recycled materials can support circularity by replacing natural aggregates, their use may lead to trade-offs in pavement performance, such as reduced

Table 5
Pairwise comparison of circularity indicators provided by DM1.

CIs	I_1	I_2	I_3	I_4	I_5	I_6	\tilde{w}^s	\bar{w}
I_1	AI	VHI	VHI	AHI	AHI	AHI	(0.84,0.16,0.12)	0.271
I_2	VLI	AI	AI	AI	AI	AI	(0.47,0.45,0.38)	0.144
I_3	VLI	AI	AI	SLI	SLI	SLI	(0.42,0.55,0.33)	0.128
I_4	ALI	AI	SHI	AI	SHI	SHI	(0.52,0.46,0.32)	0.163
I_5	ALI	AI	SHI	SLI	AI	AI	(0.47,0.49,0.34)	0.146
I_6	ALI	AI	SHI	SLI	AI	AI	(0.47,0.49,0.34)	0.148

$$CR_{DM_1} = 0.095$$

Table 6
The result of the aggregate and normalized weights at each level.

Cls	Aggregate weights	w_i	CSs	Aggregate weights	w_{ij}	CFs	Aggregate weights	w_{ijk}			
I ₁	(0.66,0.33,0.25)	21.19 %	I ₁₁	(0.58,0.40,0.30)	27.52 %	I ₁₁₁	(0.55,0.39,0.35)	51.55 %			
						I ₁₁₂	(0.52,0.41,0.35)	48.45 %			
						I ₁₂₁	(0.58,0.39,0.31)	36.46 %			
			I ₁₂	(0.49,0.49,0.32)	22.40 %	I ₁₃	(0.54,0.44,0.31)	25.33 %	I ₁₂₂	(0.51,0.47,0.32)	30.94 %
									I ₁₂₃	(0.53,0.43,0.33)	32.60 %
									I ₁₃₁	(0.60,0.37,0.32)	55.69 %
									I ₁₃₂	(0.49,0.47,0.34)	44.31 %
			I ₁₄	(0.53,0.45,0.30)	24.75 %	I ₂₁	(0.56,0.40,0.34)	53.84 %	I ₁₄₁	(0.55,0.41,0.34)	51.01 %
									I ₁₄₂	(0.53,0.43,0.34)	48.99 %
									I ₂₁₁	(0.61,0.36,0.30)	54.35 %
									I ₂₁₂	(0.53,0.44,0.32)	45.65 %
			I ₂	(0.51,0.47,0.32)	15.42 %	I ₂₂	(0.49,0.46,0.35)	46.16 %	I ₂₂₁	(0.58,0.40,0.29)	26.22 %
									I ₂₂₂	(0.59,0.39,0.30)	26.97 %
						I ₃	(0.51,0.47,0.32)	15.34 %	I ₃₁	(0.54,0.41,0.34)	51.15 %
I ₂₂₄	(0.54,0.43,0.31)	24.44 %									
I ₃₁₁	(0.66,0.32,0.28)	41.79 %									
I ₃₁₂	(0.49,0.47,0.32)	29.98 %									
I ₃₁₃	(0.47,0.49,0.33)	28.23 %									
I ₃₂₁	(0.58,0.38,0.33)	54.16 %									
I ₃₂₂	(0.50,0.45,0.35)	45.84 %									
I ₄₁₁	(0.74,0.25,0.24)	47.17 %									
I ₄	(0.59,0.41,0.28)	18.38 %	I ₄₁	(0.72,0.26,0.24)	43.91 %	I ₄₁₂	(0.46,0.49,0.35)	26.97 %			
						I ₄₁₃	(0.44,0.51,0.35)	25.86 %			
						I ₄₂₁	(0.51,0.44,0.34)	32.42 %			
			I ₄₂	(0.47,0.49,0.33)	26.81 %	I ₄₃	(0.51,0.46,0.32)	29.29 %	I ₄₂₂	(0.51,0.44,0.34)	32.57 %
									I ₄₂₃	(0.55,0.40,0.34)	35.01 %
									I ₄₃₁	(0.56,0.42,0.31)	34.87 %
			I ₅	(0.43,0.56,0.29)	12.85 %	I ₅₁	(0.55,0.42,0.32)	25.96 %	I ₄₃₂	(0.58,0.39,0.32)	35.68 %
									I ₅₁₁	(0.60,0.36,0.32)	56.48 %
						I ₅₂	(0.55,0.41,0.33)	26.34 %	I ₅₃	(0.46,0.51,0.32)	21.38 %
I ₅₂₁	(0.59,0.40,0.29)	26.64 %									
I ₅₂₂	(0.49,0.49,0.30)	21.92 %									
I ₅₂₃	(0.60,0.38,0.30)	27.17 %									
I ₅₂₄	(0.54,0.44,0.31)	24.27 %									
I ₅₃₁	(0.54,0.42,0.33)	49.81 %									
I ₅₃₂	(0.54,0.42,0.33)	50.19 %									
I ₅₄₁	(0.56,0.40,0.34)	53.13 %									
I ₆	(0.54,0.44,0.29)	16.82 %	I ₅₄	(0.55,0.41,0.33)	26.32 %	I ₅₄₂	(0.50,0.45,0.34)	46.87 %			
						I ₆₁₁	(0.54,0.41,0.37)	50.82 %			
			I ₆₂	(0.49,0.46,0.38)	46.74 %	I ₆₁	(0.55,0.41,0.37)	53.26 %	I ₆₁₂	(0.52,0.43,0.35)	49.18 %
									I ₆₂₁	(0.64,0.34,0.28)	37.98 %
									I ₆₂₂	(0.51,0.46,0.33)	28.78 %
									I ₆₂₃	(0.57,0.41,0.31)	33.24 %

structural strength. To meet durability requirements, this can lead to increased design thickness and ultimately greater material consumption (Hong et al., 2014). Second, regulatory limits in some countries on the allowable proportion of recycled materials in pavement construction may reduce the perceived feasibility and impact of material circularity (Mantalovas and Di Mino, 2019).

The social indicator (I₅) received the lowest assigned weight of 12.85 %, but this does not imply a lack of importance. One explanation is that the DMs in this study are primarily technical experts, whose work focuses more on environmental and technological dimensions. Additionally, in the current phase of circular economy adoption in pavement construction, social performance is often considered a secondary outcome. It is shaped by improvements in environmental quality, cost efficiency, and technological implementation, rather than being a direct target of implementation. This tendency is also observed in other sectors. For example, Vimal et al. (2021) applied the fuzzy AHP method to assess CE practices in manufacturing organizations and found that the social indicator received the lowest weight, accounting for only 10 %. These findings suggest that, compared to other indicators which bring measurable and immediate benefits, social outcomes are perceived as indirect and long-term, and thus may receive less emphasis at early stages of an evaluation framework. However, from a long-term perspective, the social dimension remains essential. It directly reflects the interests of diverse stakeholders, and is critical for achieving

systemic coordination in the transition toward a circular economy in pavement construction.

4.2. Meso-level circularity index

Step 1: Establish the grade matrix The grades provided by the 11 DMs were compiled to form a grade matrix R_{ijk} for each circularity factor, as detailed in Appendix A. For analytical purposes, the average values of the R_{ijk} grade matrix (\bar{R}_{ijk}) derived from the 11 DMs are presented in Table 7 in Step 2.

Step 2: Calculate the grade matrices for circularity standards and indicators Using w_{ij} and w_{ijk} from Table 6, combined with the grade matrix R_{ijk} for each circularity factor, and applying Equation (7), the grade matrices were calculated. Table 7, prepared for subsequent calculations and analysis, presents the grade matrices R_i for each circularity indicator, along with the averages \bar{R}_i , \bar{R}_{ij} , and \bar{R}_{ijk} for each circularity indicator, standard and factor.

According to Tables 6 and 7, despite circular economy system design (I₁) having the highest weight of 21.19 %, it received the lowest average grade of 0.521, particularly underperforming in the system characteristics standard (I₁₁), which scored only 0.468. This finding agrees with Piñones et al. (2023), who identified poor performance in deconstruction and resource recovery methods within pavement construction

Table 7
Grade matrix results for circularity indicators and circularity standards.

Cls	R_i	\bar{R}_i	CSs	\bar{R}_{ij}	CFs	\bar{R}_{ijk}			
I ₁	[0.499,0.498,0.535,0.573,0.490,0.520,0.593,0.168,0.615,0.499,0.735]	0.521	I ₁₁	0.468	I ₁₁₁	0.464			
					I ₁₁₂	0.473			
			I ₁₂	0.557	I ₁₂₁	0.509			
					I ₁₂₂	0.636			
					I ₁₂₃	0.536			
			I ₁₃	0.524	I ₁₃₁	0.536			
					I ₁₃₂	0.509			
			I ₁₄	0.540	I ₁₄₁	0.518			
					I ₁₄₂	0.564			
			I ₂	[0.470,0.546,0.618,0.753,0.500,0.753,0.527,0.135,0.665,0.470,0.479]	0.538	I ₂₁	0.502	I ₂₁₁	0.527
								I ₂₁₂	0.473
						I ₂₂	0.579	I ₂₂₁	0.555
								I ₂₂₂	0.645
						I ₃	[0.562,0.454,0.575,0.690,0.577,0.690,0.583,0.121,0.548,0.562,0.447]	0.528	I ₃₁
I ₃₁₂	0.555								
I ₃₁₃	0.591								
I ₃₂	0.486	I ₃₂₁	0.527						
I ₄	[0.505,0.680,0.646,0.658,0.709,0.658,0.677,0.383,0.795,0.505,0.608]	0.620	I ₄₁	0.626	I ₄₁₁	0.700			
					I ₄₁₂	0.555			
			I ₄₂	0.595	I ₄₁₃	0.564			
					I ₄₂₁	0.491			
					I ₄₂₂	0.609			
			I ₄₃	0.636	I ₄₂₃	0.682	I ₄₃₁	0.664	
							I ₄₃₂	0.564	
							I ₄₃₃	0.691	
I ₅	[0.331,0.759,0.724,0.778,0.795,0.772,0.600,0.387,0.735,0.369,0.746]	0.636	I ₅₁	0.559	I ₅₁₁	0.527			
					I ₅₁₂	0.600			
			I ₅₂	0.678	I ₅₂₁	0.682			
					I ₅₂₂	0.664			
					I ₅₂₃	0.618			
			I ₅₃	0.546	I ₅₂₄	0.755	I ₅₃₁	0.518	
							I ₅₃₂	0.573	
I ₅₄	0.742	I ₅₄₁	0.764	I ₅₄₂	0.718				
				I ₅₄₃	0.718				
I ₆	[0.344,0.711,0.609,0.784,0.593,0.784,0.658,0.218,0.760,0.344,0.653]	0.587	I ₆₁	0.568	I ₆₁₁	0.527			
					I ₆₁₂	0.609			
			I ₆₂	0.609	I ₆₂₁	0.627			
					I ₆₂₂	0.627			
					I ₆₂₃	0.573			

projects. Similarly, Mantalovas et al. (2020) highlighted significant gaps in circular economy system design at the macro-level, emphasizing the need for cohesive strategies to integrate circular principles into pavement construction. These findings reinforce the necessity of comprehensive system design guidance to address these shortcomings. Furthermore, the material circularity indicator (I₂) and cost circularity indicator (I₃) also showed poor application grades, scoring 0.538 and 0.528, respectively (refer to Table 7). The low performance of the material circularity indicator is consistent with Mantalovas and Di Mino's micro-level observations, which revealed substantial challenges in material reuse at the end of its lifecycle in pavement construction (Mantalovas and Di Mino, 2019).

In contrast, the social indicator (I₅), despite being assigned the lowest weight of 12.85% (Table 6), achieved the highest average grade of 0.636, as detailed in Table 7. It particularly excelled in the standards related to companies (I₅₂) and contribution (I₅₄), with scores of 0.678 and 0.742, respectively (Table 7). These findings agree with Piñones et al. (2023), who also observed strong performance in social indicators. This outcome implies that circular economy practices in pavement construction are currently making a significant positive impact on pavement construction companies' reputations and social responsibility, despite their relatively lower priority in the model.

Combining weights and grades (Tables 6 and 7), the results highlight strengths in environmental (I₄) and technical (I₆) indicators, which align

closely with their perceived importance. Both achieved consistent grades of 0.620 and 0.587, respectively. These two indicators excelled in areas like greenhouse gas emission control (I₄₁) and process efficiency (I₆₂). This indicates that under the current policy requirements, these two indicators have received increased investment and innovation during construction processes, reflecting their critical role in enhancing circular economy practices.

Step 3: Meso-level circularity index matrix Using the weights w_i for each circularity indicator from Table 6 and the R_i values calculated in Table 7, the meso-level circularity index matrix was determined according to Equation (6), as shown in Equation (10).

$$CI = \sum_{i=1}^n w_i \times R_i = [0.457, 0.601, 0.611, 0.696, 0.602, 0.684, 0.608, 0.232, 0.685, 0.462, 0.616] \tag{10}$$

Step 4: Calculate Meso-level circularity index Based on the result of Equation (10), Equation (11) illustrates the calculation of the meso-level circularity index for pavement construction, using the weighted average described in Equation (7).

$$\bar{CI} = \frac{1}{n} \times CI \times 100\% = 56.9\% \tag{11}$$

The current circular economy performance of the macro-level pavement management system across Europe is primarily between 40% and 60% (Wasiq and Golroo, 2023). To clarify the evaluation of the circularity index in the pavement construction sector, benchmark standards for the meso-level circularity index for pavement construction were established based on previous studies (Vimal et al., 2021; Garrido et al., 2023). Table 8 provides the details of the benchmarks.

In the field of pavement construction, the results obtained from evaluations by pavement construction companies, consulting firms, and circular economy experts indicate that the pavement construction circularity index is 56.9%. According to Table 8, the concept of the circular economy has been moderately implemented in the pavement construction sector, but further improvements are still needed. Compared to the study by Piñones et al. (2023), which applied Circularity indicator of the urban road projects (CIROAD) model to three

Table 8
Benchmark levels for Meso-level circularity index in pavement construction.

Circularity Index Range	Levels	Description
[0%, 20%]	Limited Circular Economy Implementation	No circular system exists; there is no focus on material reuse, environmental or social impacts, or circular technologies. No economic return is generated.
(20%, 40%)	Preliminary Circular Economy Implementation	Basic recycling or reuse efforts are present, but minimal integration of circular principles and low economic benefits.
(40%, 60%)	Moderate Circular Economy Implementation	Circular practices, including material reuse, are moderately applied with some environmental and social consideration, generating modest economic returns.
(60%, 80%)	Advanced Circular Economy Implementation	Circular economy system is well-integrated, with significant material reuse, attention to impacts, and strong economic benefits, though some challenges remain.
(80%, 100%)	Comprehensive Circular Economy Implementation	A fully optimized circular system with high resource efficiency, minimal waste, thorough impact consideration, and consistent economic returns.

urban road projects of the Chilean Ministry of Housing and Urbanism in Santiago Metropolitan region of Chile and reported circularity indices of approximately 20 % based on evaluations from a single public sector client organization. This study provides a broader perspective and greater reference value for assessing the current state of circular economy practices in the pavement construction industry.

Overall, the calculated meso-level circularity index is 56.9 %, indicating that, while circular economy practices have been applied to some extent, particularly in environmental and social aspects, significant improvements are still needed in system design, material circularity, and economic returns to enhance the overall circular economy performance in pavement construction.

Step 5: Sensitivity analysis To ensure the robustness of the meso-level circularity index for pavement construction calculated through the SF-AHP method, a sensitivity analysis was conducted. In this sensitivity analysis, the weights of the six key circularity indicators were systematically adjusted from 0 to 1, increasing by 0.1 each time, and new alternative circularity index was calculated using Equation (8). When the weight of one circularity indicator was adjusted, the weights of the remaining circularity indicators were proportionally allocated according to their original importance. This adjustment simulates potential shifts in policy from being entirely disregarded (weight of 0) to being fully prioritized (weight of 1), while maintaining the existing applications of circular economy. The purpose of this full adjustment range is to observe the effect of varying indicator weights on the overall circularity index, thus providing an assessment of the model's stability and robustness in response to potential changes in policy. This approach offers insights into the model's resilience under diverse weighting scenarios likely to be encountered in practical applications.

In this study, the circularity index \overline{CI} results, obtained by adjusting the specific weight of each indicator according to Equation (8) are shown in Fig. 3. The linear relationship between changes in circularity index values and weight adjustments for all six indicators arises from the weighted sum calculation in Equation (8), where adjustments to weights linearly scale each indicator's contribution to the overall circularity index. The radar chart in Fig. 4 illustrates the corresponding sensitivity coefficients S , which represent the impact of each indicator on the model's sensitivity.

Sensitivity analysis evaluates the impact of weight adjustments for six circularity indicators on the overall circularity index. As shown in Fig. 3, environmental circularity indicator (I_4) and social indicator (I_5)

exhibit the highest sensitivity, with steep positive slopes indicating their significant influence on the circularity index as their weights increase. This observation is further supported by Fig. 4, where the radar chart highlights the large and dynamic areas for these two indicators. Notably, the sensitivity coefficient of the social indicator exceeds 1, underscoring its dominant role in driving circularity performance. In contrast, cost circularity indicator (I_3) and technical indicator (I_6) display flatter slopes in Fig. 3, indicating minimal sensitivity to weight adjustments. This is confirmed by their smaller, less variable regions in Fig. 4, reflecting their secondary role in influencing the index.

Material circularity indicator (I_2) and cost circularity indicator (I_3) present moderate contributions, as evidenced by their gentle slopes in Fig. 3 and relatively uniform distributions in Fig. 4. These indicators play consistent, foundational roles, providing systemic and material stability to the circularity index. In summary, the sensitivity analysis highlights the robustness of the meso-level circularity index model for pavement construction. The findings, as illustrated in the figures, underscore the critical need to prioritize environmental and social factors, which exhibit the highest sensitivity, while maintaining the system and material dimensions as integral foundations for achieving sustainable outcomes. The model's resilience, except for isolated scenarios where unusually high weights are assigned to single indicators, assures its reliability for practical applications. This adaptability ensures the model can accommodate variations in expert weight assignments influenced by evolving policy, making it a forward-compatible tool for real-world decision-making in circular economy.

5. Conclusion

5.1. Summary

In recent years, road pavement as an essential infrastructure for transport, has been associated with significant environmental impacts and depletion of natural resources, placing immense pressure on the industry to adopt sustainable practices. This highlights the urgent need to promote the CE within the sector. Nevertheless, at the meso-level, there is a lack of clear frameworks and indicators to guide stakeholders in determining directions in future development. To address this gap, this study developed a three-level conceptual model based on literature analysis, policy interpretation, and expert discussions and feedback. This model aims to help stakeholders understand, evaluate, and promote the implementation of circular economy practices. Using input from 11 DMs representing three different types of stakeholders in the UK, the EU and China, the study employs the SF-AHP framework to analyze the relative

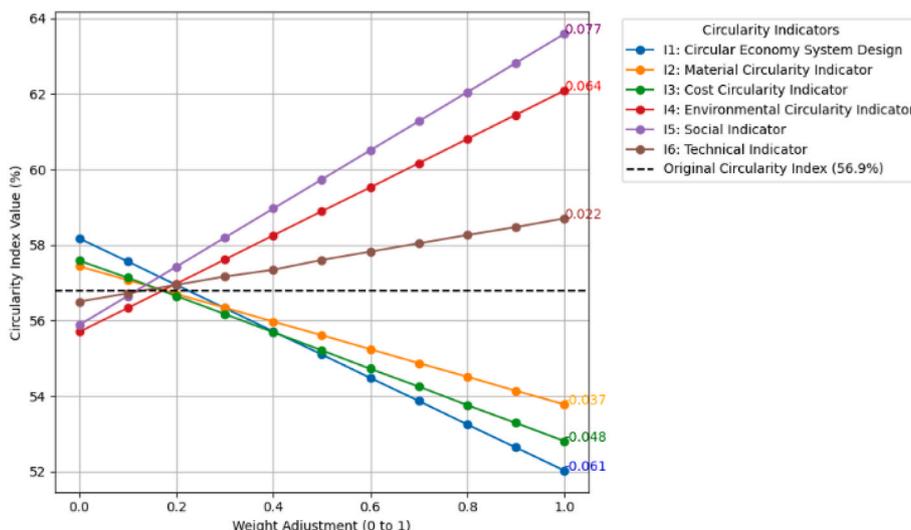


Fig. 3. The impact of variations in each circularity indicator on the circularity index.

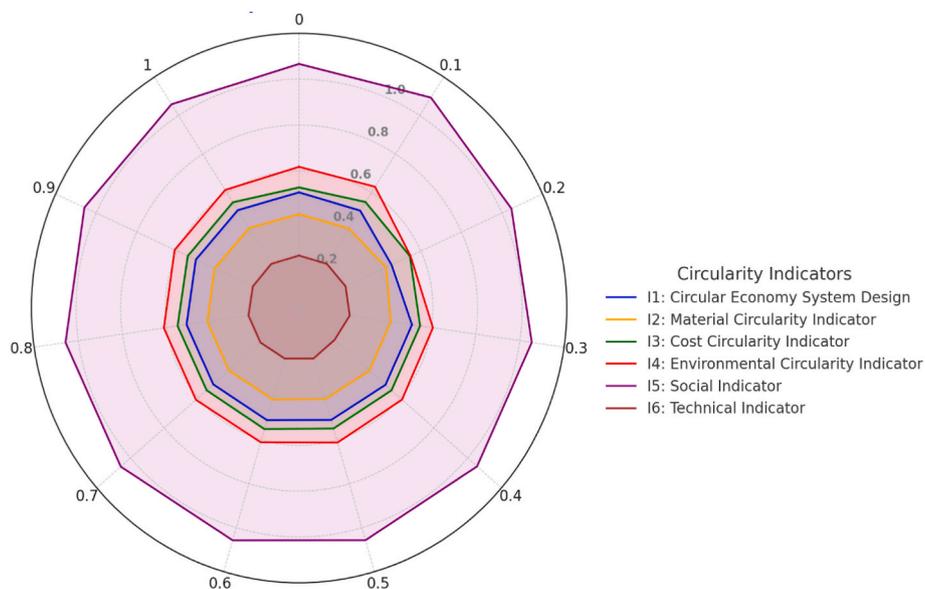


Fig. 4. Sensitivity coefficient results for circularity indicators.

importance of weights of each level and assess the performance of circularity factors in current pavement construction practices.

The results reveal that the current meso-level circularity index is 56.9 %, indicating a moderate level of circular economy development and application within the industry. Circular economy system design is identified as the most critical factor for the industry's sustainable development, with the highest weight. However, its implementation score is relatively low, particularly due to the lack of a comprehensive system for ensuring material circularity throughout the lifecycle during the design phase. Material and cost indicators also show less optimistic results, likely constrained by current policies and technological limitations. The lack of financial incentives, investment mechanisms, and supportive regulations limits the use of recycled materials. Future policies should address these barriers through targeted subsidies, procurement standards, and technical guidance to enhance circular practice implementation. These outcomes highlight how weaknesses in circular economy system design can influence other dimensions, reinforcing the importance of a coordinated and comprehensive implementation strategy. Conversely, environmental and technical indicators have high weights and demonstrate relatively strong implementation performance, particularly in achieving notable outcomes in the context of carbon reduction. These two indicators play a vital role in improving the recovery efficiency of circular materials and reducing environmental impacts, which indirectly enhance social outcomes.

While the social indicator achieved the highest implementation score, it was assigned the lowest importance weight. This gap may be partly attributed to the technical background of the DMs, but it also reflects the evolving nature of social impacts in the early stages of CE implementation. Circular economy practices have already begun to generate positive outcomes for various stakeholders, particularly pavement construction companies and the wider community through improved sustainability and contributions to broader societal goals. The social indicator is often underweighted in early evaluations, as also observed in other sectors such as manufacturing (Vimal et al., 2021). However, as material, environmental, technical, and cost-related circular strategies become more established, attention is likely to shift toward social performance as an integral dimension of long-term CE transition, a tendency that is also reflected in the results of the sensitivity analysis. These findings underscore the role of regulatory mechanisms in reinforcing the inclusion of social dimensions within long-term circular economy strategies in the pavement construction sector, thereby advancing more holistic sectoral transitions.

This research addresses a critical gap in the literature by proposing a three-level conceptual model for meso-level circular economy evaluation in the pavement construction sector. The model integrates 6 circularity indicators, 17 circularity standards and 44 circularity factors, providing a comprehensive framework to assess the current state of circular economy implementation and promote sustainable development within the industry. By employing the SF-AHP methodology for the first time in the meso-level evaluation of the pavement construction sector, within a multi-national and multi-stakeholder context, the study ensures precise weighting and demonstrates strong alignment with existing macro-level findings, highlighting the model's applicability and relevance to the broader industry context. Additionally, a sensitivity analysis conducted in this study demonstrates the robustness of the proposed model, indicating that despite changes in the weight ranges of various indicators, the core conclusions remain consistent, further validating the model's applicability and reliability in evaluating meso-level circular economy practices.

Existing macro-level studies at the national pavement management system level in Europe indicate that circular economy performance is currently only moderate (Wasiq and Golroo, 2023). Positioned at the meso-level, the framework developed in this study shows that the pavement construction sector, as an essential component of those systems, is in a similarly moderate stage of circular economy implementation. Compared with the macro-level index, which necessarily remains more aggregated, the present framework provides more detailed insight into the specific gaps in circular economy implementation across the pavement construction sector for each circularity indicator. In this way, it complements macro-level assessments by offering sector specific diagnostic information that can support the refinement of national and regional pavement strategies and guide future micro-level decisions, with the circularity factors highlighting where additional efforts are most needed.

Beyond these analytical contributions, the findings also have practical implications for different stakeholder groups in the pavement construction sector. For practitioners in pavement construction firms, particularly those responsible for design, procurement and maintenance, the combination of a high weight but only moderate implementation level for circular economy system design, together with the middling performance of the material and cost indicators, is noteworthy. In practical terms, firms can first strengthen system level circular design by planning a lifecycle wide circular framework for each pavement project and using it to guide material recovery and reuse at

both the construction and end of life stages. In terms of materials, they can, within the limits of existing standards, gradually increase the use of recycled materials and build on the relatively strong environmental and technical foundations revealed by this study by adopting more efficient processes and equipment to improve energy and resource efficiency. These adjustments can help maintain or improve pavement performance while progressively enhancing the economic performance of circular practices and reducing long term resource use and potential social costs.

For enablers such as technology providers, design firms and academia, the results on material and cost circularity confirm that the use of recycled materials is still constrained by limited technological maturity. Technology providers can focus on improving the performance and reliability of recycled materials and the efficiency of production and construction processes in line with the social and environmental indicators, helping to reduce the practical barriers faced by contractors when adopting circular solutions. Research and investment priorities can also be directed towards more durable pavement solutions, such as epoxy asphalt, which extend pavement service life and thereby reduce material use and cost over the full lifecycle (Sun et al., 2025).

At the policy level, the results suggest three main priorities for regulators and public authorities in the pavement construction sector. First, circular economy policies need stronger promotion and enforcement, so that multi lifecycle design requirements and material loop planning are clearly specified and effectively implemented in practice. Second, incentives and funding programs for advanced technologies and circular materials should be introduced, supporting research, pilot projects and wider deployment of high performance recycled and innovative materials in line with the material, cost, environmental and technical indicators. Third, supervision of end-of-life pavement waste and recycling systems should be enhanced, for example by setting minimum recovery and recycling targets and planning dedicated circulation routes for reclaimed materials, so that intended circular flows are realized on the ground rather than remaining only at the design level.

Overall, this study provides an evidence-based evaluation for meso-level circular economy assessment in the pavement construction sector and offers a framework that can be adapted to other infrastructure sectors in future research and practice.

5.2. Limitations and areas for further work

This research, while comprehensive, is limited by its reliance on DMs' evaluations across diverse regions with varying levels of regulatory support for circular economy practices. Additionally, the data in this study is dependent on assessments provided by DMs, which may introduce biases or inaccuracies due to differences in expertise, subjective judgement, or incomplete information. These limitations highlight the need for more diverse data sources and complementary methods to validate findings. The inclusion of a broader range of stakeholders, particularly in economically underdeveloped countries and regions, would help ensure global applicability and provide a more representative evaluation of circular economy implementation.

To address these limitations, future research could consider integrating micro-level data from specific pavement construction projects to complement meso-level evaluations. By calculating circularity indices at the micro-level and establishing connections between micro- and meso-level assessments, researchers could mitigate the potential biases in DM-based evaluations by informing DMs of the micro-level circularity study results. Similarly, results from meso-level CE study can be used to adjust the weighting of impact categories, an optional step in micro-level LCA.

Another promising direction for future studies is to apply the sector oriented meso-level framework to different regional pavement construction systems and to derive meso-level circularity index that reflects the specific stage of circular pavement development in each context. Such applications would enable a more targeted evaluation of circular

economy practices while mitigating inconsistencies that may arise due to differences in technological advancement and implementation standards across countries or regions. At the same time, although the proposed framework encompasses a structured set of circularity indicators, standards and factors derived from current literature and expert consultation, it may not fully capture all emerging indicators. Given the rapid evolution of CE assessment approaches, future studies could expand the framework by integrating new dimensions, provided they align with the defined sectoral boundaries and preserve conceptual integrity.

Lastly, future research can explore and rank the barriers hindering the promotion and implementation of circular economy practices in the pavement construction sector based on the proposed model. This approach would help identify critical obstacles, providing policymakers and industry practitioners with clear priorities and actionable strategies to enhance circular economy adoption and performance.

CRedit authorship contribution statement

Songfeng Shen: Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Yue Huang:** Writing – review & editing, Supervision, Methodology. **Angelica Salas Jones:** Writing – review & editing, Supervision, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2026.147557>.

Data availability

Data will be made available on request.

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