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CirCrete: A multi-criteria performance-based decision support framework for end-of-life management of concrete

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ABSTRACT

In response to the need for a smooth transition from a linear economy, circularity strategies are gaining attention within the construction industry. While the circularity strategies for concrete, which is the most widely used construction material, are well known, there is a paucity of research about their practical implementation for end-of-life (EOL) management of concrete structures. In this study, a novel performance-based decision support framework named 'CirCrete' is proposed to facilitate a holistic approach for integrating the circular economy strategies for EOL management of whole concrete structures. The core of the framework is based on three broad circularity strategies that include: refurbishing, remanufacturing, and recycling. A set of indicators developed from a sustainability perspective are integrated in the framework to facilitate the comparative evaluation of the different circularity strategies for concrete. An Excel spreadsheet is provided to illustrate the utility of CirCrete. The applicability of the framework is demonstrated in two case studies exemplifying the three circularity strategies for EOL management of concrete. The first case study considers a hypothetical UK office building that demonstrate the application of CirCrete when adopting remanufacture or recycling/landfilling route, with the consideration of eight different scenarios. The second case study presented is based on an actual refurbishment project in the UK to demonstrate the application of CirCrete when implementing a refurbishment route. The results obtained highlighted the capabilities of CirCrete in providing optimal solution for EOL management of concrete and a classification system developed for rating circularity.

1. Introduction

Circularity models of material use have rapidly gained attention with thousands of publications emerging every year to explore ways to ensure a smooth transition from the linear to the circular economy. One important area of focus is the concrete industry, where circularity initiatives can be implemented to minimise material use and extend material loops [1]. The strategies used to promote circular thinking are crucial for the built environment to reduce the widely reported environmental impacts of using concrete in construction [2]. These strategies include, among others, designing and specifying concrete with a focus on reducing material usage, producing durable concrete that can be maintained, repaired, refurbished, reused, or remanufactured, and recycling concrete to close the material loop [3]. By adopting these strategies, the concrete industry can reduce waste and increase material efficiency while contributing to a more sustainable future for concrete products such as buildings, road pavements, earth retaining structures, shore barriers, dams, embankments, and other infrastructures.

Until now, most studies presenting research on the circularity principles in the end-of-life (EOL) stage of concrete have focused on reprocessing construction and demolition waste as recycled materials, as exemplified in previous studies [4,5]. These applications include crushing concrete to produce recycled aggregate or using fines as a partial replacement of virgin feedstocks for clinker production. Although this approach is favoured by industry, and is now enabled by the recent inclusion into the European standards EN 197–6 [6] and guidance [7], for example in cement production with recycled building materials; efficient material separation is challenging, practical implementation remains under development, and it remains largely unknown what factors control the final product performance [8,9]. Moreover, following the hierarchy of resource efficiency through circularity does not, especially in reinforced concrete applications, ensure a more sustainable use considering emissions and cost [10]. As an example, for producing a concrete with similar specification of strength and durability, but using recycled concrete aggregates instead of natural ones, it

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Nomenclature

List of Abbreviations

EOL	End-of-life
LCA	Life cycle assessment
LCI	Life cycle inventory

Notation/Symbols

β_k	represents the weight of the *kth* indicator
C_j	represents the *jth* cost component
C_T	represents the total cost
E_{AC}	represents the environmental impact associated with a cradle-to-site and EOL stages
E_D	represents the environmental impact associated with LCA module D
E_i	represents the environmental impact associated with the *ith* LCA module
E_{net},	represents net environmental impact indicators
I_c	represents the composite circularity metric
I_k	represents the kth indicator value
λ	a constant that accounts for the proportion of recoverable concrete components in structures
LFI	Linear flow index
MCI	Material circularity indicator
N_k	represents the normalised value of the *kth* indicator
SL_{new}	Service life required by new application of a reclaimed concrete component
SL_{res}	Service life of a reclaimed component
R_{net}	represents net resource efficiency indicators
R_{AC}	represents the resource efficiency associated with cradle-to-site and EOL stages
R_D	represents the resource efficiency associated with LCA module D
R_i	represents the resource efficiency associated with the *ith* LCA module

is necessary to increase the binder content, which in turn will increase the allocated CO_2 emissions and cost of the final concrete product [11,12].

Accordingly, circular initiatives such as deconstruction and disassembly operations are being increasingly advocated at the EOL of concrete structures for reuse of concrete structural elements [13]. However, this concept is not new. Early accounts of the reuse of precast structural elements in Germany, as well as large scale exploration of the reuse of precast concrete panels application are reported between 1967 and 1999 [1]. Additional accounts of the reuse of precast concrete parts in a storey building in Germany and Sweden have also been identified [14–16]. In the case of cast-in-situ elements, the first account for reuse was reported for the Udden project in Sweden where several substructure and superstructure elements were harvested to be used in a new building [17,18].

Achieving concrete reuse in practical terms is not straightforward due to the variety of challenges that could impede its implementation. One of the main challenges is the lack of standardisation across industries and sectors on component recovery and re-specification [19,20]. Clear protocols and guidelines to ascertain functional performance of reclaimed components are yet to be established. To explain further, lack or inaccessibility of detailed information about the mix design of the concrete used in each project, and in many instances lack of monitoring of such structures for performance estimation. Also, current demolition practices present a barrier in standardising operations because even if there is the will to try to recover concrete components, it can be an impossible logistic task if not properly coordinated and planned with the contractor tasked with the demolition process. The implication of lack of standardisation is that different organisations deploy unclear protocols for technical evaluation of the reclaimed components for reuse in a new application [21], which can lead to confusion and inconsistency. But the mandatory implementation of digital product passport in the EU by 2027 [22] could be crucial in resolving some of the issues in standardisation. While crucial, delimiting the reusability of materials via digital product passport risks prescriptiveness due to geographic variability in the availability of secondary materials. Thus, flexibility, supplemented by explanatory notes and third-party verification, akin to environmental product declarations, could offer a potential solution. Another challenge is the difficulty in identifying opportunities for reuse, as well as assessing the feasibility and cost-effectiveness of these opportunities [1,3,23]. In addition, there may be regulatory, legal, or socio-cultural barriers that make it difficult to change established practices and mindsets around concrete reuse [20]. In this case, the disposition of construction stakeholders towards the adoption of reclaimed concrete components for reuse indicates a reluctance for both specifying and adoption in new construction for structural application [23].

Nonetheless, besides the established barriers to the widespread adoption of the reuse strategy for reclaimed concrete components including the lack of standardisation across industries and sectors [19,20], the cost-effectiveness and environmental benefits from concrete reuse are not established yet with certainty. By evaluating several reported case studies [1], it was inferred that the cost effectiveness of the construction process for concrete reuse is inconclusive. While fourteen cases reported cost benefits ranging from 10 to 78 % reduction, six cases reported higher cost implication range from 10 to 54 %. The reported wide variability is due to the heterogeneity in the system boundaries, assumptions and nature of the different concrete structures and concrete elements included in the scope of the various analyses. Similarly, the potential reduction in environmental impact of reusing EOL concrete elements instead of new ones shows a wide variability. It has been reported [24,25] that savings in terms of global warming potential ranging from 44 to 90 % for reclaimed concrete components is possible.

The need to resolve these challenges impeding the practical implementation of circular strategies for EOL management of concrete has gradually gained attention in the literature. Yet, practical implementation frameworks for achieving a circular concrete at a whole building level remains elusive till-date, despite growing efforts in this regard [13], including CEN/TC 350, CEN/TC 350/SC 1 and CEN/CLC/JTC 11, which respectively support sustainability assessment, circular economy, and public procurement for the built environment [26]. The existing efforts are reflected in the form of frameworks developed to provide a practically robust approach for EOL management of concrete but has been inefficient.

To fill this knowledge gap and advance the existing state-of-knowledge for a circular EOL management of concrete, this study proposes a multicriteria decision support framework. The framework represents a significant step change, because it is the first framework integrating all the current circularity strategies of concrete, offering a consistent decision-making process for EOL management of concrete. The study is structured as follows: a review of existing frameworks for concrete circularity assessment is presented to establish the research gaps, after which the framework design and description is presented. Furthermore, a validation has been included using case studies. The implementation is done using an excel spreadsheet, which is included as supplementary file to demonstrate the computations when considering an actual project. This serves both the methodological contribution of harmonising the sustainability assessment process, and the empirical contribution of understanding the limits of recently promoted decarbonisation strategies for reinforced concrete structures that focus on maximising reuse as a strategy. The framework provides a practical tool that can facilitate the implementation of policies, such as the UK circular economy policy [27].

2. Literature review: existing frameworks for concrete circularity and research gaps

2.1. Evaluation of circularity

Despite strides in transitioning from a linear to a circular economic model for concrete, there is a notable dearth in the development of quantitative tools to operationalise circularity strategies [28–30]. Notably, several reviews have analysed and reported various use of circularity indicators for evaluating the move towards a circular economy [31–34]. Yet, limitations such as lack of robustness of the indicators have been consistently acknowledged. Some of these include among others, overemphasis on a single dimension of circularity, inability to capture aspects of environmental impact, inability to capture circular economy complexities which hampers industry application, wrong attribution of benefits such as in the linear flow index (LFI) and material circularity indicator (MCI) that attributes recycling and reuse an equivalent benefit [35,36].

Consequently, these issues necessitate the adoption of indicator sets that can capture the multi-dimensionality of circular economy [37]. Within this space, indicator sets that represent the three pillars of sustainability (economic, environment and social) have been most widely adopted in multicriteria circularity evaluation [38]. Even so, the social dimension still demands further attention as the focus is often economic and environmental aspects [35]. There is also a paucity of indicators, dealing with the circular options of reuse, repair, and maintenance due to overemphasis on recycling [35]. Existing initiatives focusing on indicators for reuse potential in cement and concrete primarily operate at a material level, as demonstrated in a study evaluating the reuse of presumed 'waste' materials [39]. However, this approach has limitations, particularly in neglecting factors such as the physicochemical or mineralogical attributes of the material or product design [39].

To effectively determine the reuse potential of concrete, a product-level assessment is essential, considering the inherent characteristics of the structural elements and their state at the time of reuse [40]. In this sense, the product-level refers to wholly integrated components such as in buildings and infrastructures, while the individual concrete components refer to structural elements such as a beam, column, among others, which follows a similar nomenclature in other studies [3,36,38]. Establishing a reliable protocol that incorporates both the physical and chemical changes that concrete elements can undergo during their service life is imperative. A comprehensive evaluation of concrete sustainability at the product level should encompass environmental performance characteristics such as embodied carbon and energy emissions, and intrinsic concrete engineering behaviours such as strength and durability [41,42] that integrate safety of the concrete structure for reuse, a social dimension to sustainable circular economy practice. Ultimately, the economic aspect can be reflected in terms of cost benefit of implementing circularity for concrete. This triple bottom line sustainability perspective is consistent with the consensus in the circular economy literature on the representation of economy, social and environmental pillars via cost, safety, and carbon emission respectively [35].

Importantly, the potential EOL management options for a circular concrete at the product level have been clearly highlighted to include three reutilisation options (i) refurbishment – fixing of relevant degraded components in a whole structure, (ii) remanufacture – extraction of reusable components from a whole degraded structure. Fig. 1a provides a visual explanation for refurbishment and remanufacture. (iii) concrete recycling – which is well explained in previous research [3,43] and the basic steps are visually represented in Fig. 1b. However, these circularity strategies are distinct from each other. A systematic hierarchy and a holistic assessment for implementation when considering the EOL management for a whole structure has not been well articulated previously.

2.2. EOL frameworks

Sustainability assessments often rely on theoretical frameworks, which can be adapted for circularity evaluation. However, the absence of firmly established standards for implementing circular economy poses challenges. Notably, BS 8001:2017 [44] is a widely referenced standard (e.g. Ref. [45]) that advocates for a system-level approach to exploring circularity within organisations. Prior to this, various individual standards were developed to promote eco-design, resource efficiency, and waste prevention. Moreover, the European Commission has taken steps towards advancing circularity through the European Union Levels framework, which includes an assessment tool focusing on resource efficiency and circular materials lifecycle for buildings through its macro-objective 2 [46]. The framework is underpinned by four indicators in the form of (i) bill of quantities, (ii) materials and lifespan construction and demolition waste, (iii) design for deconstruction and

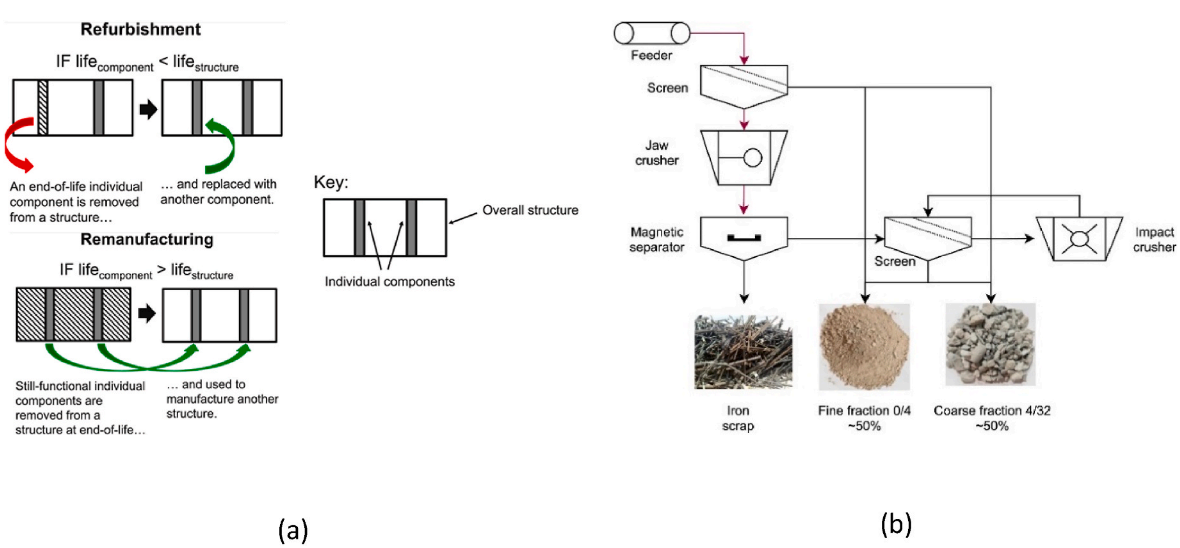

Fig. 1. *Circular end-of-life management options for concrete structures: (a) Reutilisation options, reproduced from* Ref. [3] *(b) Recycling option, reproduced from* Ref. [43].

(iv) design for adaptability and renovation. Additionally, the PAS 2080 [47], developed by a joint industry partnership, encourages carbon management in buildings and infrastructure, supports circularity by encouraging the quantification of all emission and removal sources during the whole life of an asset within and beyond the system boundary. Its elements of circularity include refurbishment/retrofit, reuse, repurposing, and waste management, albeit lacking clear implementation guidelines for EOL concrete in the accompanying guidance document. The International Standards Organisation is currently working on a standard for measuring and assessing circularity performance, which has just been published in 2024 [48]. Consequently, previous studies evaluating circularity for concrete EOL have adopted existing approaches for sustainability assessment, mainly life cycle assessment (LCA) [49]. The approaches that have been applied in precedent studies have been presented and reviewed here. Table 1 summarises the reviewed EOL frameworks that have been previously applied to concrete and indicates that previous research on EOL management for concrete lacks a holistic approach and the management options have been predominantly selected based on preference.

Eberhardt, Birgisdottir and Birkved [50] analysed five EOL scenarios for concrete components focused on reuse and recycle. The conclusions of this work were that the new application for the recovered concrete components influences the energy and emissions relative to a baseline scenario, in which the embodied impacts were found to reduce in all the circular scenarios [50,51]. Moreover, the considered reuse EOL management for different concrete elements of the building including floor slabs, core walls, roof slabs, columns and beams showed that about 23–60 % savings in embodied impacts are possible [50]. The assessment assumed a predetermined design for disassembly scenario with allocated percentages of various concrete elements' recovery rate as determined by a demolition company. Furthermore, Samarakoon and Ratnayake [52] analysed five EOL scenarios for precast concrete components and a decision on the optimal scenario was made based on multicriteria analytic hierarchy process. However, these frameworks preclude an explicit demonstration of the interrelationship and interdependence of the scenarios evaluated. Another study modelled the effect of different EOL scenarios for concrete wall components in a new product system relative to a conventional new concrete wall [53]. As before, scenarios were simply predefined because it is easy to perform the analysis at the component level to avoid the intricacies of a holistic product level assessment for a whole concrete structure. On attempting the practical application of the European Union levels framework for assessing the circularity options for a building, it was shown that in managing construction and demolition waste, the materials and elements can be either recycled or reused at best [54].

Arguably, the most comprehensive framework developed for design for deconstruction in whole building assessment was presented by Akbarnezhad, Ong and Chandra [55] and captures various circular scenarios such as reuse, recycle and landfilling scenario using a computer aided design tool. However, the structure of the framework is linear, meaning that simultaneously considering all the applicable circularity scenarios for concrete is not possible, in addition to the fact that the framework is generalised for buildings and neither captures the specificities of concrete such as durability performance nor the refurbishment option in the EOL management.

Another comprehensive framework was developed for considering reuse and recycling options specifically for concrete, with a focus on reusability cycle (via durability assessment) [10]. However, as in the approach proposed by Ref. [55], the EOL scenarios were predefined. In addition, for analysis of a simple concrete component, the proposed unified system boundary for the framework is somewhat complicated because it attempted to incorporate different cycles of reuse in the system boundary which introduces uncertainty, and the outcomes varied with the conventional LCA approach. Moreover, the framework is dependent on the Fick's law of diffusion, also in concrete terms referred to as square root of time for representing all concrete degradation mechanisms, which is not always the case because concrete has other deterioration mechanisms that affect durability, which cannot be described by diffusion-control mechanisms.

Until now, research has focused on the evaluation of predefined, distinct EOL management for concrete without an integrated decision framework for the EOL management decision making and explicitly exclude the refurbishment scenario. Also, precedent studies have mainly focused on single concrete components and a decision-making framework at the whole building level is lacking. In response to the existing knowledge gaps, this study centres on answering the research question - how to decide the most circular use of concrete at EOL considering multi-sustainability criteria? This is achieved by proposing a novel framework to enable the decision-making process to determine the sustainability and suitability of EOL reinforced concrete management alternatives, accounting for intrinsic properties of the EOL concrete. The rationale of the proposed framework design and description are presented. Case studies demonstrating the applicability of the framework are also discussed. For the implementation of the framework, a user-friendly excel spreadsheet has been used, which is included as a supplementary file to demonstrate the calculation of the CirCrete indicators (presented in section 3) when considering an actual project. Furthermore, the more sophisticated decision support systems are often limited to multi-criteria decision analysis. However, the Excel tool simultaneously combines Building information modelling information, LCA and multi-criteria decision analysis to inform the decision making. Thus, the tool is specifically suited to the problem of decision making for end-of-life management of concrete for various circularity scenarios.

3. CirCrete framework design

The framework was designed with the aim to provide a clear workflow for each circular EOL management alternative, which facilitates the simultaneous consideration of all the circularity strategies. The need for the proposed holistic approach has been clearly highlighted while presenting the technical barriers for the implementation of circularity strategies for concrete [3]. For instance, there will always be a trade-off between design for reuse and recycling, because each respectively facilitate geometrical standardisation and geometrical optimisation.

Table 1
Summary of existing EOL frameworks for concrete.

Short title	EOL options for evaluating concrete circularity					Assessment scale	Reference
	Refurbish	Reuse	Repair	Recycle	Landfill		
Framework for building designed for disassembly	×	✓	×	✓	✓	Concrete components	[50,51]
Framework for EOL solution prioritisation of precast concrete	×	✓	✓	✓	✓	Concrete components	[52]
Framework comparing carbon emission from circular & conventional building components	×	✓	×	✓	×	Concrete components	[53]
EU Level framework indicators for circularity	×	✓	×	✓	✓	Different building components	[54]
Framework for assessing deconstruction strategies	×	✓	×	✓	✓	Different building components	[55]
Framework for LCA assessing reuse & recycle strategies for concrete	×	✓	✓	✓	✓	Concrete components	[10]

Hence, it is crucial to explore conditions (e.g., durability performance via service life considerations for a certain exposure condition) under which one is optimal compared to the other.

The workflow for implementing a multicriteria based evaluation of EOL concrete circularity is outlined in Fig. 2. The rationale is based on the integration of different circularity strategies for concrete as proposed by Marsh et al. [3], and builds upon the existing frameworks summarised in Table 1. The objective is to allow the user to compare the outcomes of all circular scenarios for which the relevant data is available. Importantly, the multicriteria CirCrete indicators that have been proposed for decision making are typical indicators for assessing circularity within the framework of LCA and life cycle costing. The indicators are selected from a sustainability perspective and include environmental impact indicators, namely carbon emission and energy demand. Resource efficiency indicator in the form of resource use (e.g., input materials, including waste), and an economic indicator in the form of cost (including material cost, site activity cost and transportation cost), while a social dimension of safety of the structure is intrinsically incorporated in the framework design in terms of mechanical performance and durability assurance (see Fig. 2).

These indicators have been adopted considering the state-of-the-art in concrete circularity [52,55] and reported case studies [56]. The selected indicators are also considered as the most relevant and commonly applied to enable concrete circularity while considering a sustainability perspective. However, while these indicators are the most applied when considering circularity of concrete in previous studies, it is important to note that these indicators have been selected similarly here for demonstrating the framework. Therefore, they are not fixed and should be ultimately decided by the multiple stakeholders involved in a project development with appropriate justification for the opted indicator choices. For example, the framework may be adapted to emerging EOL concrete scenarios. Also, social indicators such as safety of site operation [52] can be included depending on the interest of the project stakeholders. Thus, such social indicators have been excluded in the presented hypothetical case study as they are often qualitative and more apt in actual projects.

Thus, circularity measurement using the considered CirCrete indicators for the circular actions of refurbish and remanufacture can be computed using Equations (1)–(5):

$$E_{net} = E_{AC} - \lambda E_D \tag{1}$$

$$E_{AC} = \sum_{i}^{m} \lambda E_i \tag{2}$$

$$R_{net} = R_{AC} - \lambda R_D \tag{3}$$

$$R_{AC} = \sum_{i}^{m} \lambda R_i \tag{4}$$

$$C_T = \sum_{j}^{n} \lambda C_j \tag{5}$$

Where E_{net}, R_{net} and C_T respectively represents net environmental impact indicators, net resource efficiency indicators and total cost; E_D and R_D respectively represent the environmental impact and resource

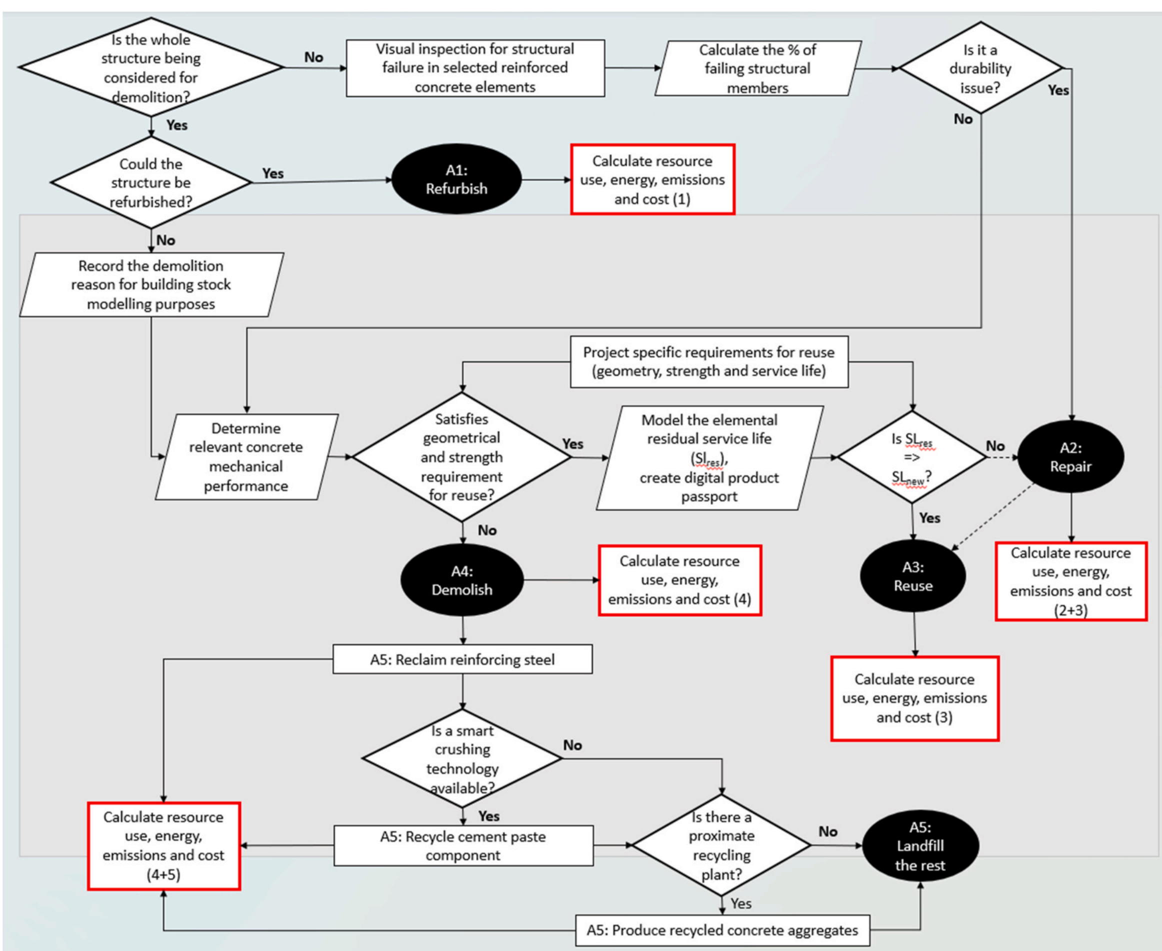

Fig. 2. Proposed multicriteria performance assessment framework for EOL concrete. At each stage, the indicators are calculated and compared with a new build scenario before deciding on the actual circular strategy to be adopted.

efficiency associated with LCA module D; *i* represents the environmental impact associated with LCA modules A1, A2, A3, C1, C2, C3 and C4; *j* represent the cost associated with material, transport and construction activity; λ is a constant that accounts for the proportion of recoverable concrete components in the structure.

After the computation of the individual measurement indicators, aggregation is used to compute a composite circularity metric in accordance with existing sustainability assessment frameworks [57] as shown in Equation (6). Prior to the aggregation, the indicators are normalised using Equation (7) as follows:

$$I_c = \sum_{k=1}^{p} \beta_k N_k \tag{6}$$

$$N_k = \frac{max\, I_k - I_k}{max\, I_k - min\, I_k} \tag{7}$$

Where I_c is the composite circularity metric, β_k represents the weight of the *kth* indicator, N_k is the normalised value of the kth indicator, I_k is the kth indicator value as computed from Equations (1), (3) and (5). The computation formulas similarly apply to new build, recycle and landfilling scenarios. However, new build scenario includes only the LCA modules A, recycle scenario includes only modules C and D, while the landfill scenario includes only module C.

The decision-making process commences with identifying whether the structure to be evaluated will be demolished or not. If the answer is no, in line with the schematic (Fig. 2), the refurbishment route is explored, or else, if the response is yes, the remanufacture route is then explored. Both routes end up in the recycling/landfilling route when the desired project requirements for both refurbishment and remanufacture are not attainable.

In the following sections of this work the different scenarios included in the decision-making framework proposed are described in detail.

3.1. Refurbishment route

One of the options of the proposed framework is establishing if the structure can be refurbished or not. Several factors need to be considered to make such decision including (i) Is the concrete structure yet to reach a threshold age (30 years) to require replacement [50,56]? which is based on recommendations of previous research [51,58]; (ii) Again, as stipulated in previous research [40,59], if demolition is being considered because of a change in functional requirement, can the structure be refurbished so that it can be adapted for a new functionality [40,57]? (iii) Is there sufficient foreground information about the structure such as engineering drawings and material specification details, often denoted as material or product passport, as described in previous research [52,60,61]?

If the response to these questions is yes, then refurbishment is considered comparatively with a new build (which is the baseline scenario) using the multicriteria CirCrete indicators. If the response is not, demolition/deconstruction is then explored, in which recoverable components defined herein as structural elements, are assessed against a new project requirement adjudged in terms of mechanical performance, geometrical and durability requirement. These have been reported as the crucial project requirements that need to be accounted for to ensure safe reuse of concrete [62,63].

3.2. Remanufacture route

Alternatively, if the remanufacture route is preferred when the whole building is being considered for demolition, the steps involve an initial visual inspection of the concrete structural elements. This can involve the evaluation of cracks, determining its extent or degree by measuring their width and depth [63,64]. This is a first step that helps to determine the quantity of structural elements that might be susceptible to structural failure. The crack pattern can also provide insight into the potential development of degradation mechanisms the structure might be experiencing, such as carbonation (caused by interaction of concrete with CO_2), freeze-thaw (if exposed to different seasons), chloride-induced corrosion (caused by exposure to a marine environment or de-icing salts), alkali-aggregate reaction (if reactive aggregates were used), or sulfate (particularly if the structure is exposed to sulphated soils) [63,64]. If most of the structural elements cannot be reclaimed, then the decision of demolishing might need to be made. However, if most of the structural elements can be reclaimed, then the framework recommends as the next step to assess if there is a durability concern, and if yes, the framework proposes to evaluate the feasibility of repairing such element prior to its reuse. If there is no durability concern, the framework recommends the assessment of the project specific requirements (e.g., strength, geometry, and service life) for evaluating the reuse potential. Importantly, while assessing the project specific requirements, the mechanical performance and geometrical requirements are initially assessed and if unsatisfactory, the framework recommends demolition, otherwise, the durability requirement is then evaluated based on the comparative evaluation of the residual service life of the reclaimed concrete component (SL_{res}) and the service life required by its new application (SL_{new}). Some service life modelling approaches have been specifically developed for this evaluation [63,65].

For instance, methods presenting computation formulas for estimation of the residual service life include the factor method, phenomenological models, and mathematical models (Fick's laws) [63]. In the factor method, the reference service life of the concrete structure is factored by seven coefficients that aim to account for maintenance level, usage conditions, outdoor environment, indoor environment, work execution level, design level and inherent performance level. A range of values is typically specified for different degradation mechanisms such as freeze-thaw and corrosion as per building codes. Phenomenological models are empirical relationships developed based on experimental observations such as the time order model [63]. The method is based on acceleration testing, which assumes that the in-service degradation mechanism in the field can be simulated under laboratory conditions. An acceleration factor is then derived to relate the degradation rate simulated experimentally with the long-term exposure in the field. Mathematical models for residual service life estimation are derived from transport properties and how they influence the durability of concrete using differential equations. Mathematical models that account for carbonation and chloride-induced degradation mechanisms are based on Fick's laws of diffusion.

Thus, if the service life requirement is satisfactory, then the framework recommends reuse for the reclaimed concrete structural element without any further processing, otherwise, repair (e.g., increasing the concrete cover) is made before the concrete can be reused. For each of these decision options, the CirCrete indicators are calculated, for the purpose of comparing each circular scenario with a new build. Also, the creation of a digital product passport is an output at this stage for which the concrete can go into stockpiling, if the characterised project requirements suggest that it may be relevant for a different purpose. The challenge for implementing this being that it is a complex logistic work to create concrete element warehouses/banks where people can source the reclaimed concrete.

3.3. Recycling/landfilling route

In such cases when the strength and geometrical project requirements are such that the remanufacture route cannot be followed and the decision of demolishing the structure is made, the CirCrete indicators are calculated for the steel reinforcement that will be present in structural concrete, and concrete recycling process, accounting for the efficiency of concrete recycling technology for the recovery of cement paste, also referred to as recycled powder, and recycled concrete aggregates. The indicators also account for the environmental contributions associated with the proximity of the recycling plant, in comparison with the disposal of the demolished concrete in landfill, or a combination of recycling and disposal scenarios based on the potentially recoverable quantity of materials.

The mechanical performance is critical for deciding if the EOL concrete can serve its next proposed function and given service life. This is crucial to facilitate structural concrete reuse because in structural design, to prevent failure whilst maintaining the normal function of a structure, the ultimate limit state (in terms of the ability to resist shear stresses and bending moments) and the serviceability limit state (e.g. deflection of the structural element) need to be satisfactory. For determining strength, some non-destructive approaches have been proposed in the literature, for example, in the case of compressive strength, tests like rebound hammer and ground penetrating radar technology can be used [1,24,63]. The ground penetrating radar can also assist in ascertaining the concrete cover geometry [24], which can then serve as an input for residual service life prediction [63,66,67]. The original concrete constituents required for calculating the CirCrete indicators can also be deciphered via petrographic analysis including details like binder composition, age of the concrete and aggregate type [68–70].

Nevertheless, a major challenge is deciding if the percentage of reclaimable structural elements makes the repair and reuse option more sustainable in comparison with either recycle or disposal to landfill, presenting the need for a simultaneous evaluation of the EOL management options. A previous study about assessments completed by a demolition company suggests that for a concrete building, reclaimable concrete components can range from 60 to 90 % of the whole building [50]. Through a hypothetical case study, this research will show that the percentage of reclaimable structural elements is indeed a crucial consideration in deciding the most pragmatic EOL management option.

4. Methodology for the framework application

In practical terms, implementation of the proposed circularity framework for EOL management of concrete (CirCrete) is pertinent. It is crucial to highlight that because of numerous scenario possibilities that can result in real-life application, it is impossible to demonstrate them all in this research. Thus, case studies have been considered to showcase the applicability of the framework when considering the refurbishment route, the remanufacture route and recycling/landfilling route described in sections 3.1-3.3. The choice of scenarios was made to consider as many EOL scenarios as possible, and to assess what happens when various EOL options are combined. The remanufacture and recycling/landfilling route is exemplified using a hypothetical UK case study, while the refurbishment route is demonstrated via discussion of an actual refurbishment project in the UK. These are presented in the following sections, and a freely accessible spreadsheet excel tool has been included as a supplementary file to demonstrate the implementation. The relevant data in the form of inventory used in the tool were chosen to closely represent a UK scenario to match the case study analysed. Thus, the life cycle inventory (LCI) data can be modified to suit specific contexts in other global regions.

4.1. Hypothetical case study for remanufacture and recycling/landfilling route

4.1.1. Description of an office building

In this example, an office building model was designed to demonstrate the remanufacture and recycling/landfilling route using the Mineral Product Association concept design tool [71]. The tool is open access, which can be used for structural design and selection of an optimal structural frame for concept stage design at minimum cost and carbon footprint (that is global warming potential). The assumed layout of the building is shown in Fig. 3, which comprises a framed concrete structure with 5 floors designed as two-way slabs with respective dead load, which is the load permanently borne by the structure (excluding self-weight) and imposed load of 0.5 kN/m^2 and 3.5 kN/m^2. The designated concrete compressive strength for the structural elements (slabs, beams and columns) is 30 MPa. Further details about the structural layout and design, as well as material quantities are described in the "New build case_for_reuse" tab of the supplementary file.

4.1.2. Scenarios and calculation methodology

The case study has been considered from a life cycle perspective (that is using a standardised LCA methodology) and therefore, the calculation follows the following steps described in ISO 14040/14,044 [72]:

Goal and Scope definition – The defined goal is to quantify the life cycle impacts for the concrete structural elements of the described office building. The LCA modelling was conducted in accordance with the British standards BS EN 15978 [73] and BS EN 16757 [74]. The scope involves a comparative evaluation of the upfront embodied impact of a new build baseline scenario, relative to reuse, repair, recycle and landfilling EOL scenarios for the embodied impacts, using multicriteria CirCrete indicators to identify the most plausible option. The module D (Fig. 4) is also calculated to show the relevant benefit of circularity in accordance with BS EN 15804:20,212 + A2 [75] adapting the "end-of-waste" state according to modularity and polluter pays principle [76]. This approach has been applied in related studies for EOL emission quantification [77,78]. The carbon calculations are performed to be compliant with the Royal Institute of Chartered Surveyors latest guidance document [79], but the CirCrete indicators are computed for a functional unit of internal floor area.

System boundary – The relevant system boundary for building LCA is shown in Fig. 4 with the considered modules in green and excluded

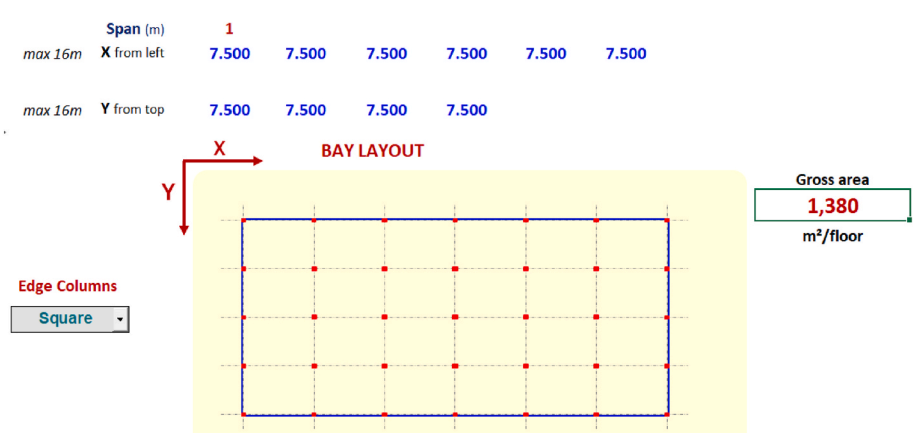

Fig. 3. Illustration from the Mineral Product Association concept design tool showing the office building layout proposed.

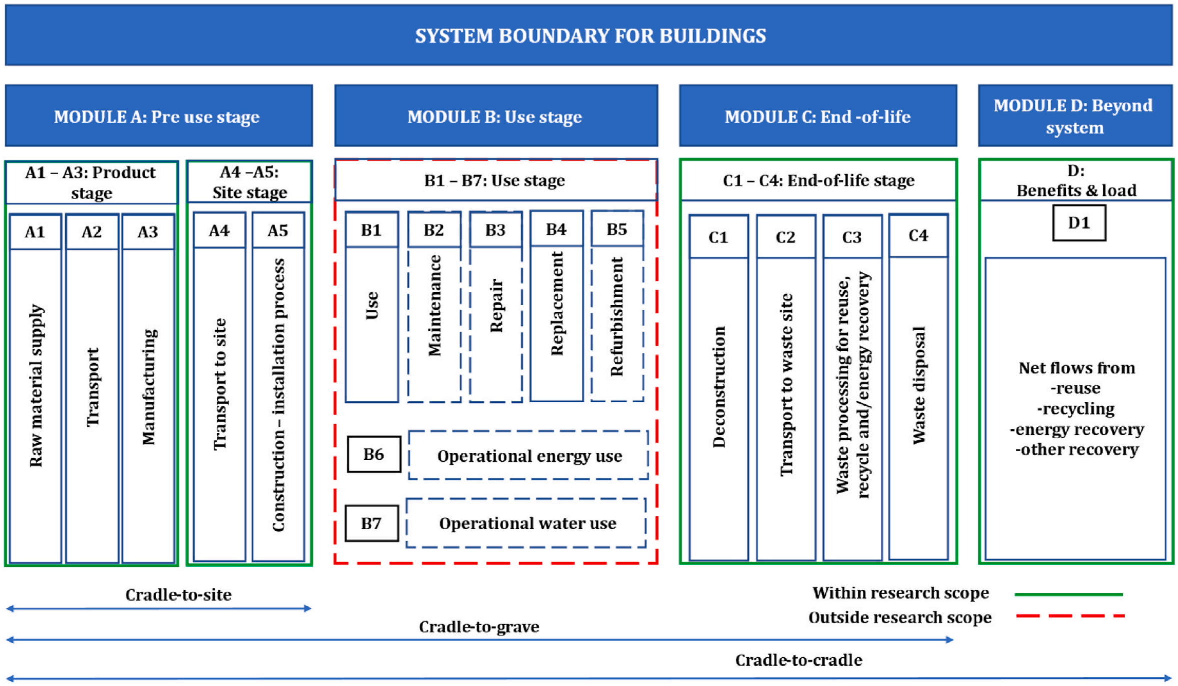

Fig. 4. System boundary considered for the remanufacture to demolition circularity scenarios for the building case scenario, according to BS EN 15978.

modules in red. Several scenarios were considered, for which different system boundaries apply and are summarised as shown in Table 2. For the deconstruct, repair and reuse scenario, the repair activity considered the replacement of the carbonated concrete cover, and the detailed calculations are presented in the supplementary spreadsheet. The internal beams, columns and all slabs were assumed to be subjected to the XC3 exposure class, and all external beams and columns are assumed to be subjected to the XC4 exposure class, in compliance with the relevant exposure class descriptions in the BS 8500–1 [80] which is a UK complement to the EN 206 [81] for specifying concrete. The concrete covers were then calculated for the corresponding structural class for a 50-year concrete service life in accordance with BS 8500 for the XC3 and XC4 exposure classes assumed [81]. In addition, it was assumed that 10 % of materials could not be recovered during the deconstruction process, and that would be required to fix the joints of the concrete elements in the new product system, as proposed in previous studies [10,53,55]. Different possible joints for concrete structural elements are reported in a previous study [1]. The 10 % is not accounted for in the current product life cycle (that is the assumed concrete at the EOL being evaluated) except for the resource use (in which waste is accounted for) because they form part of the construction embodied impacts for a new product system. Hence, functional equivalence is defined in terms of the primary materials substituted (like a recycling scenario), which is attained just after the repair activity. Likewise, the embodied impact due to transportation of the repaired concrete elements to the new site is not included in the inventory as shown in Fig. 5 and thus allocated to the new product system.

Table 2
Description of the baseline and remanufacture circularity scenarios.

Scenario ID	Description	LCA modules
S1	Baseline scenario – new build made with CEM I based concrete	A1-A5
S2	Baseline scenario – new build made with CEM II (C-M) based concrete	A1-A5
S3	All concrete elements – deconstruct, repair & reuse at EOL	C1-C4, D
S4	All concrete elements – demolish & recycle at EOL	C1-C4, D
S5	All concrete elements – demolish & landfill at EOL	C1-C4, D
S3-4	50-50 scenario – half deconstruct, repair & reuse and half demolish & recycle at EOL	C1-C4, D
S3-5	50-50 scenario - half deconstruct, repair & reuse and half demolish & landfill at EOL	C1-C4, D
S4-5	50-50 scenario – half demolish & recycle and half demolish & landfill at EOL	C1-C4, D

S3 – reuse of repaired concrete element as a reclaimed component in new application, S4 – recycle of steel and concrete as recycled concrete aggregate.

Life cycle inventory and impact assessment – The considered input-output processes for which the CirCrete indicators for the embodied impacts of the scenarios are calculated, is shown in Fig. 5, as a function of the activities linked to such impacts. Different LCI data sources have been adopted for calculating the CirCrete indicators considered for the activities shown in Fig. 5, including UK Government emission factors [82], environmental product declarations, inventory of carbon and energy version 3 database, Mineral Product Association factsheet 18, Royal Institute of Chartered Surveyors guidance document [79] and other studies [10,57,83–88]. These sources already integrated the life cycle impact assessment. The LCI data, life cycle impact assessment and corresponding sources have been detailed in the supplementary file. The calculation steps for each CirCrete indicator considered in the various scenarios and the potential sources of uncertainty in the calculations are also shown in the supplementary file.

5. Results

5.1. CirCrete indicators

The results of the computed CirCrete indicators for the relevant life cycle modules are presented in Fig. 6 as a function of the scenario type. The outcome for the carbon emission in Fig. 6a shows that the new build scenarios (S1 & S2) are the most carbon intensive, which corroborates the suggested circularity hierarchy of building nothing whenever possible [89]. Also, using a CEM II (C-M) based concrete option (S2), in which the amount of Portland cement is reduced, led to 31 % less carbon emissions in comparison with CEM I based concrete (S1). The option of disposal to landfill (S5) is the most carbon intensive EOL management option as expected, with a net positive carbon emission but has 77 % less

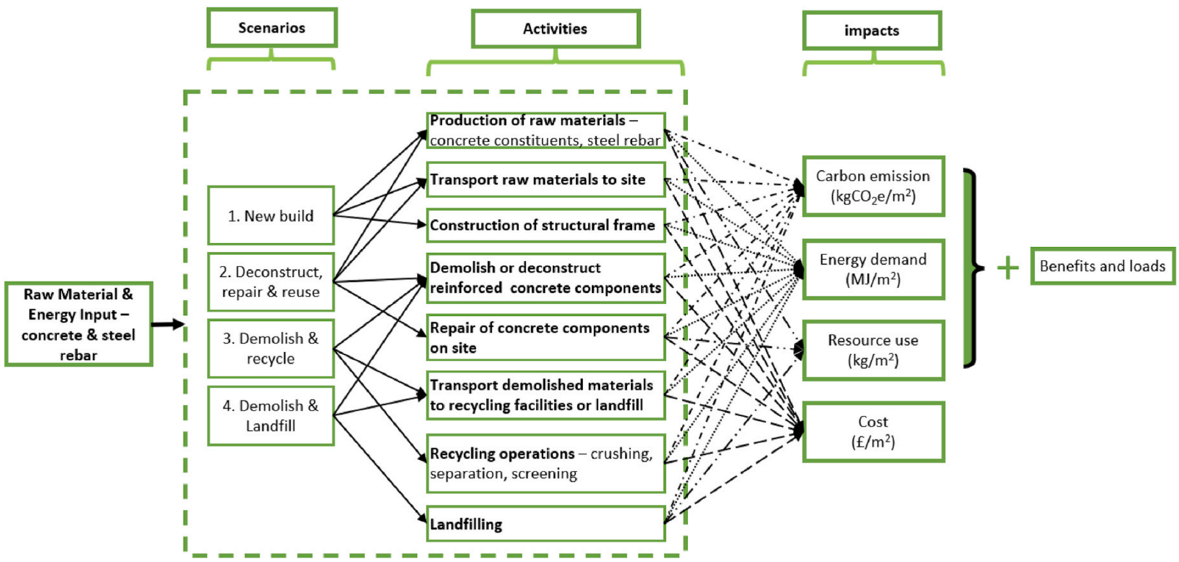

Fig. 5. Schematic representation of the inventory data for the CirCrete indicators. The dotted line indicates the scenarios and their corresponding activities that are included within the system boundary analysed for computing the associated impacts.

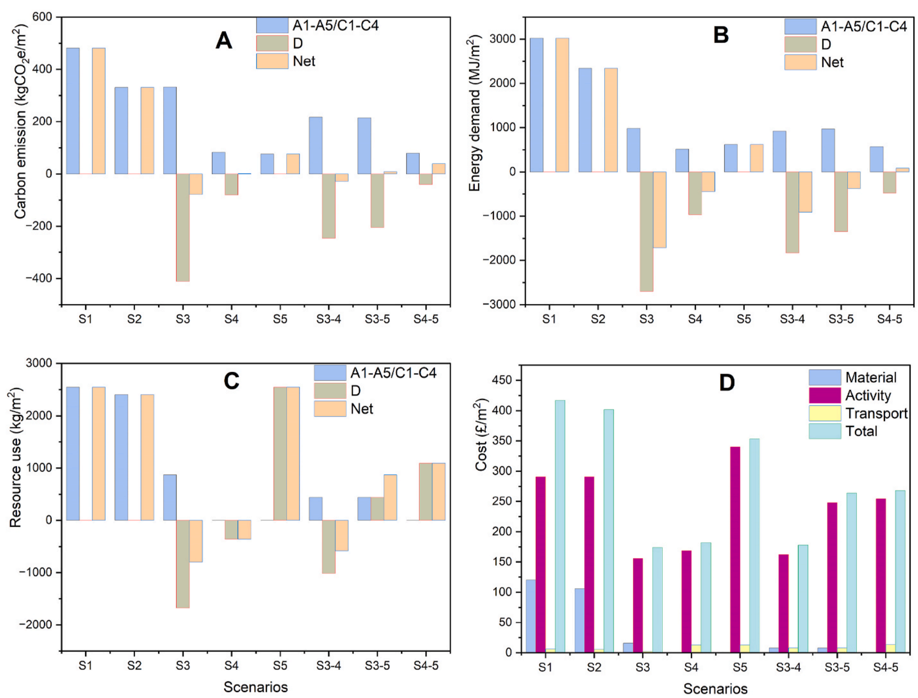

Fig. 6. Results of the scenario evaluations showing the life cycle modules for the following CirCrete indicators (a) carbon emission (b) energy demand (c) resource use (d) cost. A1-A5 apply only to the new build scenarios S1 and S2 while C1-C4 apply to the other scenarios.

emission relative to the best new build scenario (S2). The remaining scenarios had relatively less carbon emission than disposal to landfill, with scenarios S3 and S3-4 having net negative carbon emission due to the benefit of reuse as a circularity measure and the least carbon intensive scenario is the option for complete deconstruction, repair, and reuse of the structural elements in a new application (S3). The results of the carbon emission for the remanufacture circularity option is consentient with previous studies [10,52,53].

However, the benefit for the S3 scenario is only notable when circularity is considered (module D). This can be deduced from the result which indicates that S3 is as carbon intensive as the best new build scenario (S2) and about five times as carbon intensive as the landfill scenario (S5) when considering the EOL emissions only. Likewise, the EOL emissions for landfill and recycling are virtually the same (recycling emission > by 7 $kgCO_2/m^2$), but the circularity benefit of recycling over landfilling becomes prevalent when module D is included. A similar conclusion can be made for the trend of the energy demand in Fig. 6b where the scenario involving landfilling (S5) had the highest net energy demand and thus the least desirable EOL option. The remaining EOL scenarios had significantly less or net negative energy demand than the landfilling option. The results are also consistent with previous studies [52,53].

Interestingly, the result of the resource use indicator in Fig. 6c showed some slight variations from those of carbon emission and energy demand indicators. The circular scenarios that preclude landfilling (S3, S4, S3-4) resulted in net negative value of the resource use indicator, which clearly highlights the benefits of circularity. In contrast, the combination of circular scenarios with landfill option resulted in net positive value of the resource use indicator (S3-5 & S4-5). Also, while the deconstruct, repair and reuse option (S3) led to a positive value of the resource use indicator (due to repair activity) at EOL, the net resource efficiency outweighs the recycling option (S4) on the whole building scale considering the benefits of circularity. An interesting point to be highlighted however, is how both options S3 and S4 would compare with each other considering the extra materials required for integrating reclaimed components into a new building, in comparison with the additional cement requirements necessitated using recycled concrete aggregate in new concrete. However, these considerations are ascribed to the new product system and thus not considered in this study. Once again, the S3 scenario is the best economically in terms of cost as shown in Fig. 6d, while the new build scenarios (S1 & S2) are the most cost intensive. Importantly, the deconstruct, repair and reuse and recycling scenarios (S3, S4 & S3-4) are relatively comparable and consentient with related research [52]. Furthermore, the processing activities contributed the most to the cost implication, in addition to the material cost, while the transportation cost contributed minimally to the total cost (generally <8 %).

5.2. Composite circularity metric

Finally, the multicriteria evaluation of the overall circularity is represented in Fig. 7 and has been calculated by normalising each of environmental impact (carbon emission and energy demand) in Fig. 7a, resource efficiency (resource use) in Fig. 7b and economy (cost) in Fig. 7c and aggregating using equal weighting in accordance with a performance-based concrete sustainability framework as proposed by Hafez et al. [57] to obtain the composite circulatory metric in Fig. 7d. A similar approach is also recommended by the Ellen MacArthur Foundation [29]. As such, each individual CirCrete indicator is weighted as carbon emission (16.7 %), energy demand (16.7 %), resource use (33.3 %) and cost (33.3 %). It is important to highlight that the choice of equal weighting was simply to avoid bias since the presented case study is hypothetical and serves the purpose of demonstrating the core working principles of the framework. Note that, while equal weights are used in this study, the allocation of weights should be decided by the decision makers upon discussion and consideration of aspects such as local conditions and priorities. Normalisation of the indicators prior to aggregation is crucial to avoid scale effects from the embodied impacts unit variations.

The individual normalised indicator results distinctively shows how the environmental impact, resource efficiency and economy aspects vary for each of the scenarios, wherein higher values are more desirable and is consistent with the results in Fig. 6. Thus, scenario S3 is the most circular EOL management option for the case study and should be opted by the project team, if all the considerations (e.g., choice of indicators and indicator importance) are consistent with the project objectives and environmental regulations. This demonstrates a rational, systematic, and holistic approach to consider the EOL management options for the concrete building using the proposed CirCrete framework for the considered scenarios of the remanufacture and recycling/landfilling route.

Another interesting outcome shown in Fig. 7d is how the combination of different EOL management options, compare to opting a single EOL management approach. For example, the result clearly suggests that opting for the complete recycling option (S4) is much more circular than the scenario that considers reclaiming half of the concrete components for reuse and landfilling the remaining half (S3-5). This crucial observation would have been otherwise obscured if carbon emission was the only metric assessed as can be seen in Fig. 7a. This exemplifies the preeminence of the CirCrete framework in providing guidance for making the most plausible EOL decision for concrete.

Furthermore, to develop a classification guideline for the composite circularity metric developed using the CirCrete framework, this research used the Ellen MacArthur foundation circularity metric known as the MCI [29]. According to the metric, a linear flow of resources is undesirable in a circular economy, and this is measured by the LFI for which a

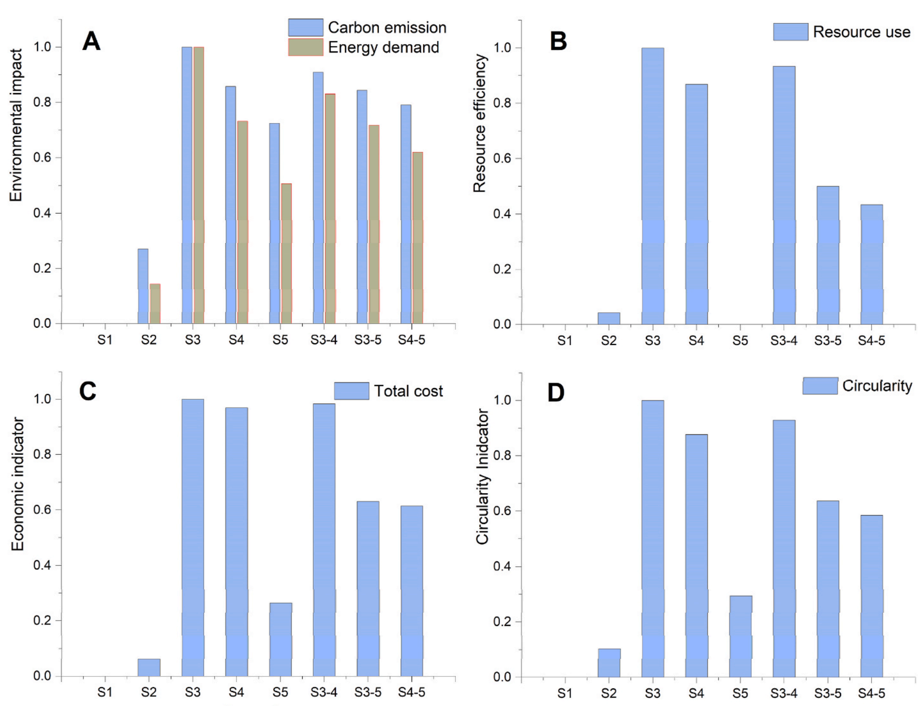

Fig. 7. Results of the scenario evaluations for normalised (a) normalised environmental impact indicator (b) normalised resource efficiency indicator (c) normalised economic indicator (d) composite circularity metric showing the final evaluation of circularity. The composite circularity metric is the aggregated composite from the application of equal weighting to the normalised magnitudes of the environmental impact, resource efficiency and economy indicator. Normalisation was done based on the scale invariant min-max feature scaling normalisation (see supplementary file), in which all the indicators were minimised.

product or material that completely matches a linear economy has a magnitude of unity and a corresponding MCI of 0.1. These metrics have been calculated for the scenarios considered in this study and shown in Table 3 and have been used as a guideline to develop a RAG (red – amber – green) rating representing linear, circular, and highly circular respectively, to measure the level of circularity achievable following an evaluation by the CirCrete framework. The calculations for the MCI and LFI were executed using an open access spreadsheet tool [90]. The results show that the scenarios S1, S2 and S5, which represent the baseline new build cases and landfilling can be regarded as linear, while scenarios S3-5 and S4-5 are circular. The highly circular scenarios are S3, S4 and S3-4. Such a simple classification system can be a useful guide to judge the level of implementation of circular economy for EOL concrete.

5.3. Sensitivity and uncertainty analyses

The method of sustainability assessment based on LCA, and life cycle costing is subject to inaccuracy when certain parameters that affect the LCI varies. This is particularly important when local conditions vary due to differences in practice across regions or differences in regulatory requirements (e.g., weighting to prioritise sustainability goals) for a specific project, which requires a sensitivity analysis to ensure reliability of the results [55,78]. There is also uncertainty in the data quality used in the LCI and the difficulty to predict future scenarios [84]. Hence, sensitivity and uncertainty analyses were conducted to verify the robustness of the composite circularity indicator computed by the CirCrete framework.

Two cases were considered for the sensitivity analysis. The first case involves three rounds of varying the transportation distances by assuming twice the transportation distance for each of reuse site, recycling facility and landfill site, keeping the others constant in each round. In the second case, again three rounds of sensitivity analysis were done to vary the impact weighting by allocating 50 % of the weight to each of environmental impact (that is carbon emission and energy demand), resource efficiency (resource use) and economy indicator (total cost), while using equal weighting of 25 % each for the other two in each round. For the uncertainty analysis, a coefficient of variation of 20 % was used for the upper and lower bounds of the input parameters including all the LCI to show the range of variability of the results.

The outcome of the sensitivity analysis is represented in Fig. 8. The effect of transportation distance on the net carbon emission in Fig. 8a is negligible, and likewise the result for energy demand in Fig. 8b, resource use in Fig. 8c and total cost in Fig. 8d. As such, the composite circularity metric in Fig. 8e show stability in the ranking of the scenarios and is consistent with the outcome of Fig. 7d. However, the composite circularity metric is more sensitive to the effect of the impact weighting as shown in Fig. 8f. The outcome of Fig. 8f suggests that scenarios S3-5 and S4-5 show minor overlap. The implication of this outcome is that the alteration of the weights may likely change their ranking order and consequently the circularity strategy opted. Nonetheless for actual projects, it is important for sustainability goals to be prioritised based on project requirements stipulated by relevant stakeholders such as town planners or policy makers. Noting that the scenarios S3-5 and S4-5 respectively combine reuse with landfill, and recycle with landfill are not in the top 3 options selected by the CirCrete framework, it is safe to say that the composite circularity metric is stable and less sensitive to certain variations in local conditions such as transportation distance and variation in weighting for the prioritisation of sustainability goals, which underlines the pre-eminence of the CirCrete framework.

Furthermore, Fig. 9 shows the impact of uncertainty in data quality and scenario assumptions on the computed CirCrete indicators. Clearly, the effect of uncertainty in the calculation of the carbon emission, energy demand and total cost in Fig. 9a, b and 9d is most significant for scenarios S1 (baseline new build), S2 (baseline new build with lower carbon concrete) and S3 (repair and reuse). The implication is that these three indicators are most impacted by slight changes in the input parameters. Particularly for total cost in Fig. 9c, there is notable overlap among scenario S3, S4 (recycle), and S4-5 (combines recycle with landfill), likewise between scenarios S3 and S3-4 (combines reuse and recycle) for carbon emission, which obscures the ranking for the selection of the most circular EOL scenario for the concrete structure.

Interestingly, the result for resource use and composite circularity indicator in Fig. 9c and e, respectively, were stable in terms of the scenario ranking and consistent with Fig. 7d, irrespective of the uncertainty in the quantification of the indicators. Therefore, within the limits of uncertainty considered (coefficient of variation of 20 %), the CirCrete framework produces a reliable and consistent estimation of the circularity. Again, the outcome of the uncertainty analysis emphasises the limitation of assuming a single environmental or economic indicator to assess circularity. This is because the results for carbon emission and total cost in Fig. 9a and d led to conflicting ranking due to overlap in the uncertainty range. The implication is that using such single indicators to evaluate circularity will increase the difficulty in the decision-making process for EOL management of concrete. This highlights the pre-eminence of the multi-criteria approach adopted in the CirCrete framework compared with that of other studies.

5.4. A real case study for refurbishment route

5.4.1. Background

The case study is described based on the accounts in previous studies [56,91]. The selected case study is the 1 Triton Square London office building refurbishment, which was originally constructed in 1998, but underwent a deep retrofit that was completed in 2021. This suggests that the building has been in-service for about 23 years at the time of refurbishment. The building aligns with refurbishment option since the building in-service lifespan is less than 30 years and the typical 50-year service life for concrete buildings as per relevant British Standards for concrete specification. The concrete therefore qualifies as not requiring replacement as recommended in previous research [51,58]. The building archetype is a seven floor above ground office building with a basement floor, which is upgraded and refurbished to a ten-floor above

Table 3
Classification system for rating the circularity of EOL concrete using CirCrete framework.

Source	Indicator	Scenario							
		S1	*S2*	*S3*	*S4*	*S5*	*S3-4*	*S3-5*	*S4-5*
Ellen MacArthur	LFI	1.00	1.00	0.51	0.52	1.00	0.515	0.755	0.760
Foundation	MCI	0.10	0.10	0.54	0.53	0.10	0.535	0.320	0.315
This study	CirCrete	0.000	0.104	1.000	0.877	0.294	0.929	0.637	0.585
	RAG scale	**Linear (<0.3)**			**Circular (0.3-0.8)**			**Highly circular (>0.8)**	

LFI – is the linear flow index. MCI – material circularity indicator. RAG – red, amber (represented by the grey colour), green rating.

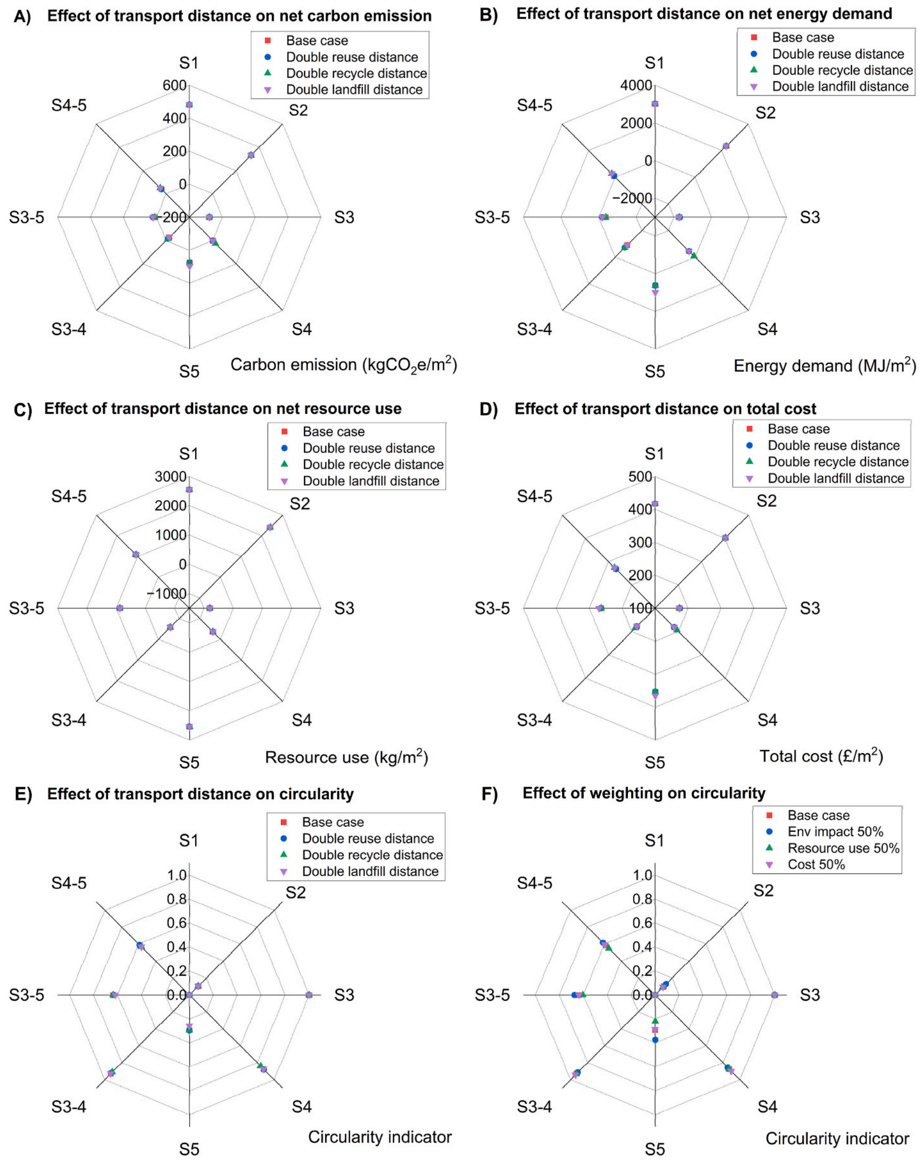

Fig. 8. Sensitivity analysis for the effect of transportation distance and variable weighting on the outcome of the CirCrete framework.

ground office building with a basement (Fig. A1 in the supplementary file). Furthermore, in addition to three new floors, the originally voided area of the central atrium was converted to useable floor area as shown in Fig. 10. This added a new gross area of 16,400 m^2, increasing the total gross floor area to 47,200 m^2. This indicates that the building is easily adaptable to a new function without requiring demolition, which aligns with the literature to repurpose the function of the building [40,59]. Furthermore, there was sufficient foreground information to safely deploy the refurbishment process. Thus, the three refurbishment criteria set out in section 3.1 are all satisfactory, supporting the refurbishment option.

5.4.2. Structural modifications

The account on the structural modifications discussed here is based on Robertson and Sturel [91]. Structural adequacy of the existing structural members was validated through back calculation of the structural capacity. The introduction of additional floors to the structural core resulted in exceeding levels of horizontal loads, which were assumed to be borne by shear walls at the basement level and eight braced steel bays in the cores. To overcome this issue, strengthening of the pile foundations, shear walls and steel columns was done. Moreover, the extant diagonal braces were replaced with new ones with increased load bearing capacity.

In strengthening the shear walls, three new shear walls were introduced at the basement to take care of additional load from earth pressures. The pile foundations were strengthened by providing supplementary piles through a piled raft solution and the load transfer mechanism was principally via Coulomb friction, interlocking and dowel action. The concrete columns were strengthened via a combination of the use of encasement and plastic fibre reinforcement. For the steel columns, the adopted strengthening mechanism was via either additional use of steel plates or concrete encasement.

5.4.3. CirCrete indicators

In the case of the 1 Triton Square refurbishment option, the engineering drawings and structural design information to make a baseline new build scenario calculation are unavailable. Thus, this research discussed the refurbishment option in terms of the individual CirCrete indicators (carbon emission, resource use & cost) but cannot aggregate to get the composite circularity metric because of the absence of a common baseline (that is, a new build scenario) to use for comparison with each of these three indicators. Nevertheless, this does not change the

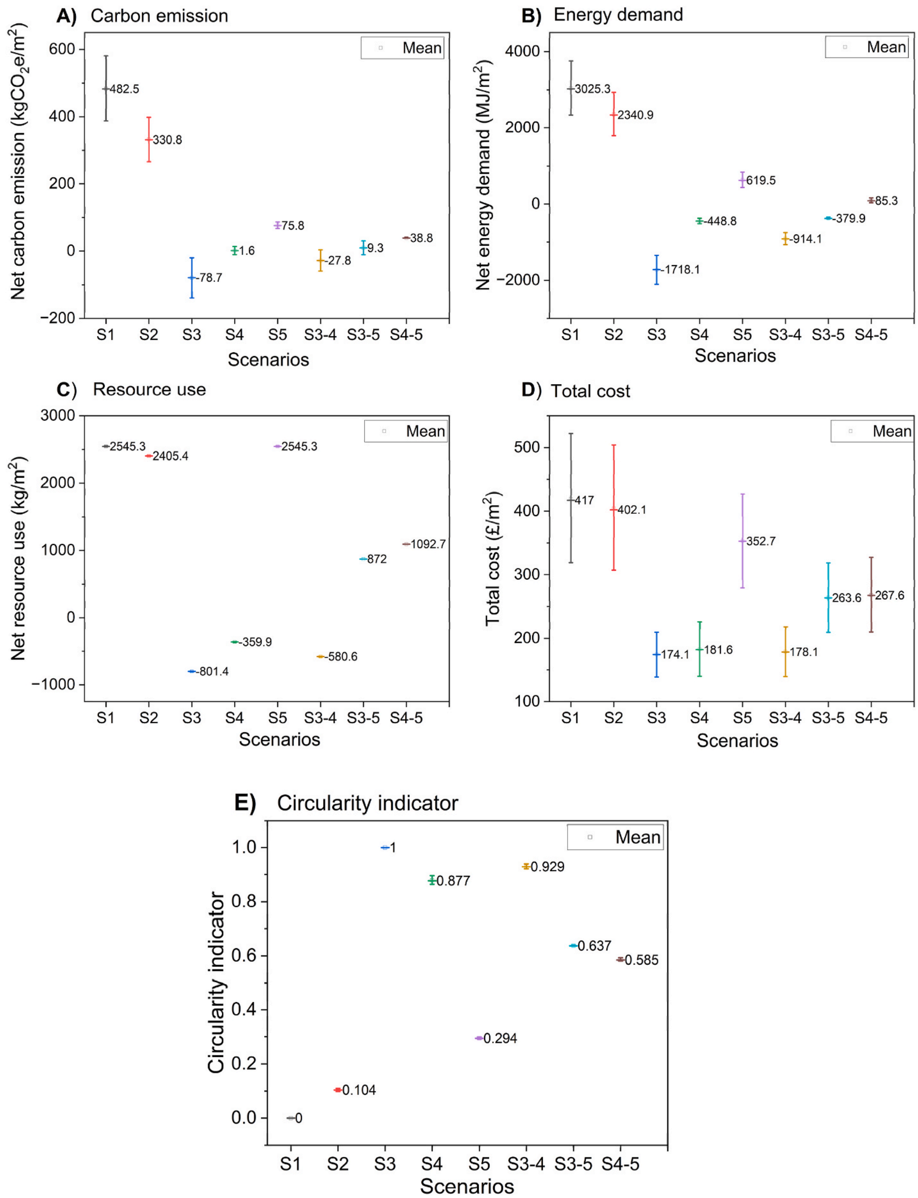

Fig. 9. Effect of uncertainty on the results and scenario ranking of the CirCrete framework.

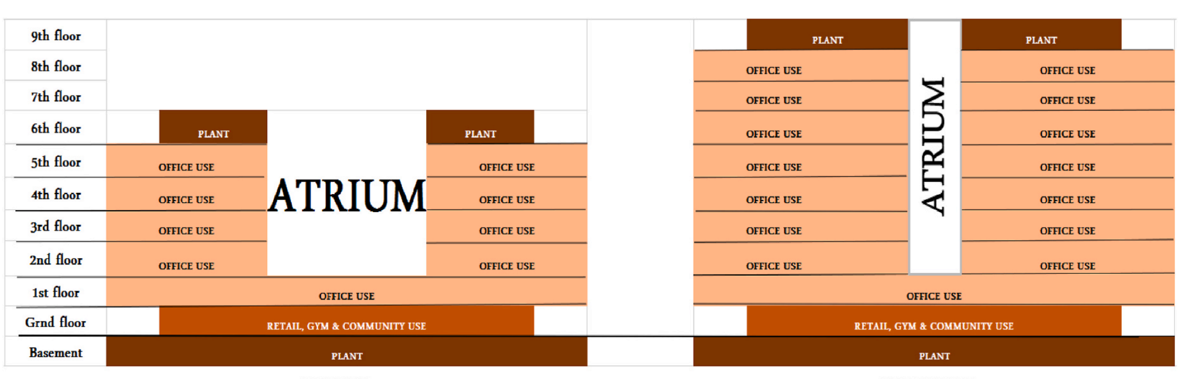

Fig. 10. *Section views of 1 Triton Square Refurbishment Project. Reproduced from* [91].

objective as the goal remains to target the minimisation of the CirCrete indicators to improve circularity. The assumptions and calculations for the indicators are further explained in Table A1 in the "Refurbishment Case Study" tab of the supplementary Excel file. Firstly, the sources of the embodied carbon (A1-A5) for the refurbishment are due to additional floors and strengthening works. Thus, the refurbishment incurred

6400 tCO_2e, which amounts to 136 $kgCO_2e/m^2$. In comparison to an equivalent benchmark new office building as per London Energy Transformation Initiative [92] with a target of <350 $kgCO_2e/m^2$ by 2030, the refurbishment amounts to savings of about 61 %. Similarly, in comparison with the Greater London Authority [93] target of <600 $kgCO_2e/m^2$ by 2030, the savings is about 77 %.

In the case of resource use, a total in-use building stock savings of 1900t of steel and 35000t of concrete was achieved, which amounts to 782 kg/m^2. In comparison with the resource savings of 801 kg/m^2 in the best scenario (S3) for the hypothetical new office building case study presented earlier, which when converted based on gross internal floor area is 160 kg/m^2, the savings from refurbishment is about five times more, which is significant. Considering the cost metric, a maximum saving of £5,000,000 was achieved from reusing the sub and superstructure, £2,000,000 from retained façade, some cost savings for regular cement replacement with GGBS and a negligible incurred cost impact. Assuming that the cement replacement cost is offset by the incurred cost, the total cost savings would be £7,000,000 and therefore 1483 £/m^2. Comparing this value with a cost value of 3220 £/m^2 for standard UK air-conditioned office building with <6 storeys [94], this amounts to a savings of 54 %. These indicators show that the refurbishment strategy is more favourable compared to a new build scenario from a circular economy perspective.

6. Discussion

Circrete is a simple, yet comprehensive framework to enable the operationalisation of circular economy principles for the built environment. The framework has several strengths, which makes it appealing and more valuable for both academic and industry stakeholders. The framework helps with early decision-making on the economic feasibility of implementing circular actions through a cost comparative analysis that can prove if circular actions can reach a break even earlier to achieve an anticipated positive return on investment in comparison with a new project. This highlights the cost savings potential of circular actions as demonstrated by the results of the study, which can help incentivise the adoption of circular options. However, as pointed out in section 3.2, the space limitation for material reserve for matching recovered components to new applications remains a barrier which can be potentially abated through related research in the field of digital supply chain network mapping to identify resource reserves and map them to their point of need.

Furthermore, CirCrete can support a niche deployment of the newly published ISO Circular Economy Standard [48] in the built environment because it not only integrates the key aspects which include circular goals and actions [95,96], circularity measurement [97] but goes further to include measuring and assessing of sustainability impacts. CirCrete supports circular goals by potentially increasing the value of end-of-life structures and integrates circular actions including refurbishment, remanufacture, reuse and recycling. The framework supports circular measurements and complementary sustainability assessment using the resource flow indicator, environmental and economic impact indicators. Beyond these, the CirCrete framework provides a tool to support policy development and education programs. For instance, the tool can serve as a decision-making tool for policymakers in implementing circular economy principles and can be used to support macro-objectives 1,2, 3 and 6 of the EU levels framework for circular economy or as an educational resource in teaching sustainability and circular economy practices in construction-related fields.

Importantly, CirCrete remains flexible to accommodate variations in local conditions by providing a performance-based workflow with user-defined inputs, which means that stakeholders can decide the most relevant considerations and adapt it to their specific situation. For example, in selecting the set of measurement indicators to consider or the weighting of these indicators for aggregating the circularity measurement in line with Ref [97] to support regional variability in environmental regulations. By incorporating the use of life cycle thinking in the circularity measurement, the generalisability and contextual adaptability of the framework, accounting for local conditions, such as differing regulations (e.g., landfill tax), and material supply chains through updating and adapting of the life cycle inventory to specific contexts.

However, despite the highlighted strengths of CirCrete, the framework can benefit from further developments. For instance, expanding the framework to account for structures comprising of composite materials such as those integrating timber and concrete and adapting refurbishment operations to integrate green spaces. This paves the way for future research that can modify the workflow of the framework for the integration of emerging circular economy strategies such as regeneration or others to achieve a more sustainable built environment. The current design of the framework precludes the incorporation of social indicators due to perceived challenges in incorporating qualitative indicators to semi-quantify social indicators and a lack of sufficient data, but future development of the framework will aim to integrate qualitative measures such as community impact, safety, or worker health, making the framework more comprehensive in terms of sustainability.

7. Conclusions and future work

In response to the imperative need for implementation of the sustainable practice of circular economy principles in the construction sector, this research introduced CirCrete, a framework for management of EOL concrete in whole building contexts. The framework is the first of its kind in adopting a holistic approach for integrating a comparative evaluation of all the potential EOL scenarios for concrete within a circular economy perspective. The framework adopts a multicriteria approach that offers a systematic decision-making workflow integrating various circularity strategies. It is on a set of environmental and economic indicators that may be derived from LCA and life cycle costing. However, the application of the framework takes a stakeholder-centric approach by ensuring flexibility in selecting indicators, weighting of sustainability goals or LCI so that any evaluation can be adapted to diverse project contexts and local conditions. The decision process unfolds through three routes: refurbishment, remanufacture, and recycling/landfilling.

Applicability of the framework was evaluated through two comprehensive case studies. The hypothetical remanufacture case employs LCA principles, revealing benefits in carbon emission, energy demand, resource use, and cost. The results demonstrated how the option of repair and reuse supersedes recycling, demolition, and new build scenarios when viewing the remanufacture EOL management option through the circular economy lenses. The real-life refurbishment case showcases the economic and environmental advantages of refurbishment over new construction, which allows achieving substantial carbon and resource savings. Both cases showcase the capacity of CirCrete to guide rational and holistic EOL concrete management decisions, contributing to sustainable construction practices and circular economy principles.

The examples presented allowed showcasing the usefulness of the CirCrete framework. Through its clear logic and implementation workflow, the framework can guide stakeholders through the complex process of decision-making and ensuring that such decisions are well-informed and aligned with broader sustainability goals through the consideration of multiple environmental and economic criteria. In addition, this framework may be used in an educational context, as it offers a practical interdisciplinary way for teaching sustainability and circular economy principles in programs related to architecture, engineering, and construction management. It can allow students to engage with the complexities and multiple variables that arise when dealing with the EOL stage of concrete.

While CirCrete showcases notable strengths, it is essential to acknowledge that challenges and limitations may arise during its application. On the one hand, practical issues, such as data availability and uncertainty, may pose obstacles. Furthermore, the success of the framework depends on stakeholder collaboration and information sharing, thus requiring commitment from all involved parties. In fact, resistance to the adoption of this kind of frameworks may be predominantly related to working cultures that are more conventional within the construction sector, but a transition towards circular approaches is encouraged by the developed framework. Furthermore, to overcome this kind of resistance, integrating multicriteria frameworks of this nature in existing standards could be helpful and can support policies such as the European Union levels framework or the UK circular economy policy.

Lastly, further refinement of the framework may be conducted from a conceptual and a practical perspective. Regarding the conceptual side, further work is needed to address specific project contexts and unforeseen circumstances, as well as societal considerations. Given the strong connection between the built environment and social impacts, including indicators reflecting factors like impacts on the local community (e.g., noise pollution, air pollution) or workers (e.g., health and safety implications of different end-of-use scenarios) is essential. Regarding practical questions, future work could focus on applying the framework in a building that is nearing its EOL stage to assess its usefulness and applicability in ex ante circumstances.

CRediT authorship contribution statement

D.C. Nwonu: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft. **I. Josa:** Methodology, Resources, Writing – review & editing. **S.A. Bernal:** Resources, Writing – review & editing, Supervision, Funding acquisition. **A.P.M. Velenturf:** Resources, Writing – review & editing. **H. Hafez:** Conceptualization, Methodology, Resources, Writing – review & editing.

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.

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Data availability

A DOI link to the University of Leeds Data repository is available here https://doi.org/10.5518/1538.

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