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ARTICLE

End-of-life solution prioritization for pre-cast concrete components aligning with circular economy targets

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Abstract

Circular economy (CE) targets provide an economic model to focus on the efficient use of resources by minimization of the waste, reduction of the linear consumption of natural resources, long-term value creation, and making material consumption circular. The building and construction sector is responsible for significantly increasing the carbon footprint and linear material consumption. The identification and prioritization of end-of-life solutions during the decommission of the existing pre-cast concrete buildings enable the carbon footprint and linear material consumption to be alleviated. The CE targets enable end-of-life solutions for structural or non/structural components to be identified, while multi-criteria decision analysis enables their prioritization using a hierarchically structured decision model. A principal challenge, therefore, is to identify the assessment criteria for such a prioritization, aligning with the CE targets, and to develop an assessment framework. This manuscript demonstrates how to prioritize end-of-life solutions using the analytic hierarchy process (AHP). The decision hierarchy has been developed using the end-of-life solutions given in research findings within the structural and/or non-structural components. The decision hierarchy development, AHP prioritization, and sensitivity analysis enable practitioners to integrate the suggested approach with building information modeling (BIM). This enhances the potential for the effective integration of the CE economic model in the construction industry and to minimize the carbon footprint.

KEYWORDS

analytic hierarchy process, circular economy, multi-criteria analysis, pre-cast concrete components, prioritization

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

1 | INTRODUCTION

Circular economy (CE) can be defined as an economic model that focuses on the efficient use of resources by minimization of the waste, reduction of the exploitation of natural resources, long-term value creation, and closed loops of linear material consumption within the boundaries of environmental protection and socioeconomic benefits.[1] To initiate the transition from a linear economy to CE, it is vital to set CE targets such as efficiency, recycling, recovery, reduction, repair, reuse, and design. Moreover, it is essential to study how to reach CE targets in day-to-day industrial practices to support sustainable development.[2] For example, nowadays, the building and construction sector has paid attention to reaching CE targets during each phase of the life cycle of a building: design, construction, service/operation, and decommission.[3] However, 60% of the raw materials are extracted for building construction, which represents 24% of these global extractions.[4] Moreover, the building and construction sector is responsible for a significant amount of CO_2 emission including 28%–39% from building facilities and operations and 11% from building materials, transport, and construction activities.[5] The recycling of a wide variety of industrial waste and its potential use as an aggregate to reduce the environmental impact of building materials and to move from a linear to circular material consumption have been discussed in the literature.[4,6,7] Similarly, the European Parliament (according to Waste Framework Directive 2008/98/EC) stated that EU countries should reach the target of recycling 70% of the construction & demolition waste (CDW) by 2020.[6] Therefore, it is vital to increase the use of recycled material while designing structures and the recovery of aggregates during the demolition phase.

To increase the recovery of material, components, and parts during the decommission stage, it is vital to consider the concept of Design-for-Disassembly (DfD) at the design stage of the structures.[8] Currently, most buildings are designed to be demolished and their materials recycled or even disposed as an end solution.[3] In addition, the optimization of the structural design would support the control of the unnecessary use of material, hence reducing the extraction of natural material.[9] Moreover, building information modeling (BIM) models, Life cycle assessment (LCA) of precast concrete products, and the concept of Material Passport (MP) are essential tools to cultivate CE thinking in construction industry.[10] However, there are few applications in published literature on how to use the BIM-based MP for selecting end-of-life-solutions.

Not only DfD but also, there is a need to adopt design-for-reassembly/reuse (DfR) concept. Huuhka et al.[11] and Dawczynski and Adamczyk[12] have discussed possible challenges to be overcome during reusing of the existing precast concrete components. Moreover, when designing connections and joints in new precast concrete structures, it is important to design for reassembly/reuse and discuss the possible reassembling scenarios for different types of buildings. Currently, the possibilities of disassembly of structural components and reassembly/reuse have not been considered in the design phase of the building. In addition, engineers have a lack of understanding about the relevant design principles for load bearing structures that can be reused because there are no design guidelines/standards.[13] Furthermore, there are limited research studies in the literature on the assessment and verification of old precast concrete structures/components for reuse.[11] It is vital to implement the concept of DfD during the structural design of the pre-cast buildings to give good access to the structural components and to minimize the time taken for disassembly. However, the time taken for dismantling and reassembling of pre-cast concrete structures is not optimized and remains unclear.

It is vital to study how to implement CE targets not only at the design stage of a building but also when a building is going to be decommissioned.[1] O'Grady et al.[14] identified two main scenarios for the decommission of a building, including a typical end-of-life scenario and the deconstruction of a building for the reuse of its parts or components. The end-of-life scenario consists of activities such as dismantling of components, movability of material/components, reusing/recycling of components, and material or disposal of the material to a landfill.[11,15,16] Moreover, compared with the end-of-life solution of recycling, the reuse of materials and components is less carbon and energy intensive and economically viable.[15] However, there are limited findings in the published research on how to select the most appropriate end-of-life solutions for a building component considering environmental, economic, technical, and societal concerns.

The selection of end-of-life solutions is a challenging task due to the lack of understanding of the use of decision analysis tools among engineers. In this manuscript, potential end-of-life solutions for precast concrete buildings are reviewed. It has been revealed that the end-of-life solution selection process is a multi-criteria decision-making process involving both quantitative and qualitative factors. Hence, a framework has been developed to show how to utilize BIM-based MPs and expert knowledge and experiences while using multi-criteria analysis (MCA) tools to make optimal decisions. The analytic hierarchy process (AHP) was selected to analysis because of its inherent capability to handle qualitative and quantitative criteria simultaneously.[17–19] The AHP analysis has been carried out using "ExpertChoice" software that has been developed based on the mathematical foundation of AHP. The AHP enables to prioritize relevant criteria and develops a consensus for making balanced decisions.[17] Furthermore, the hierarchical structure suggested for utilizing the AHP approach aids in the systematic visualization of the industrial challenge. This enables a team of engineering experts to make comparisons based on each potential hierarchy and to determine the priorities based on the criteria and sub-criteria along the AHP structure in evaluating the alternatives: end-of-life solutions.

2 | LITERATURE REVIEW

2.1 | Implementation of CE targets in the building and construction sector

The main phases in the life of a physical asset (e.g., buildings, bridges, etc.) are the concept and design, construction, service/operation, and decommission/replacement/demolition. Currently, the building and construction sector practices a linear economic model, which is basically based on the idea of "take, make, dispose of"[20] during all of the phases in the life of a physical asset. The utilization of the linear economic model can lead to depletion of resources because during the construction of any physical asset usually starting with the extraction of raw materials but restraining reuse/recycle of material used to build the structure at the end-of-life cycle.[21] For example, the majority of CDW is disposed in landfills or incinerated.[22] To move away from linear economic model and to increase recycle/reuse opportunities, the circular economy model has been widely discussed in the building and construction sector.[3,14] Moreover, CE can be defined in the context of the building and construction sector as the circular current practice of the linear economy model of consumption and production by limiting resource consumption from the environment and converting the waste generated during different phases in the life of a physical asset into value-adding products.[14] The implementation of the CE model in the building and construction sector will result in circular buildings that give positive impacts by reducing unnecessary resource depletion and environmental pollution and ensuring the preservation and growth of natural capital, social capital (i.e., health & well-being, human culture & society), as well as other value creation.[23]

The building and construction sector can implement the concept of the CE to reduce the volume of waste generation at each phase in the life of a physical asset, to preserve natural resources, to reduce demand for landfills, to improve environmental sustainability,[24] and to reduce the carbon footprint of the construction industry.[4] Hossain et al.[25] have highlighted the different aspects that are vital for successfully adopting CE in the building and construction sector, such as the use of sustainable and durable materials, adoption of DfD, usage of modular and prefabricated elements, development of recovery schemes, establishment of relevant requirements for waste and demolition plans, standards to ensure quality of the recycled materials, technical performance, recycling rate, and traceability of building materials and provision of guidelines and training for demolition companies. In addition, DfR also helps to reduce linear material consumption and CO_2 emissions. The results of implementing CE thinking within the building and construction sector are waste minimization, preservation of the quality and value of materials during operation, and reusing or recycling of building components and material at the end of the lifespan.

Gervasio and Dimova[9] have shown two main barriers to implement CE in the building and construction sector, such as the lack of appropriate design methodologies to enable a better use of construction and demolition waste and the lack of cooperation between the long chain of stakeholders in the construction process. Moreover, Benachio et al.[21] have reported that there is a lack of standardized methods and practices to implement a circular economy in construction projects. To overcome such barriers, it is vital to provide training programs/educate industrial professionals to make the most appropriate decisions while implementing CE. During the transition from a linear economic model to the CE, it is vital to uplift the engineer's knowledge to achieve optimum building/bridge design by the efficient use of resources/materials and to minimize the energy consumption throughout the life cycle of a building.[9] In addition, it is important to consider design optimization, reduction of construction and demolition waste, design for flexibility and adaptability, durability of materials and components, robustness, resilience, design for deconstruction and disassembly, and reuse/re-assembly of materials or structural components, as shown in Figure 1.[9] It is necessary to take into account the aforementioned aspects for the effective implementation of the CE model not only for new structures but also for existing structures and after the demolition of structures.

2.2 | Integration of BIM during the implementation of circular economy in the building and construction sector

The utilization of building information modeling (BIM) models enables CE thinking to be cultivated effectively within the building and construction sector.[10] Because BIM models of physical assets can carry significant amount of information about structural and non-structural components which can be used to carry out different analysis. Aguiar et al.[26] have highlighted that

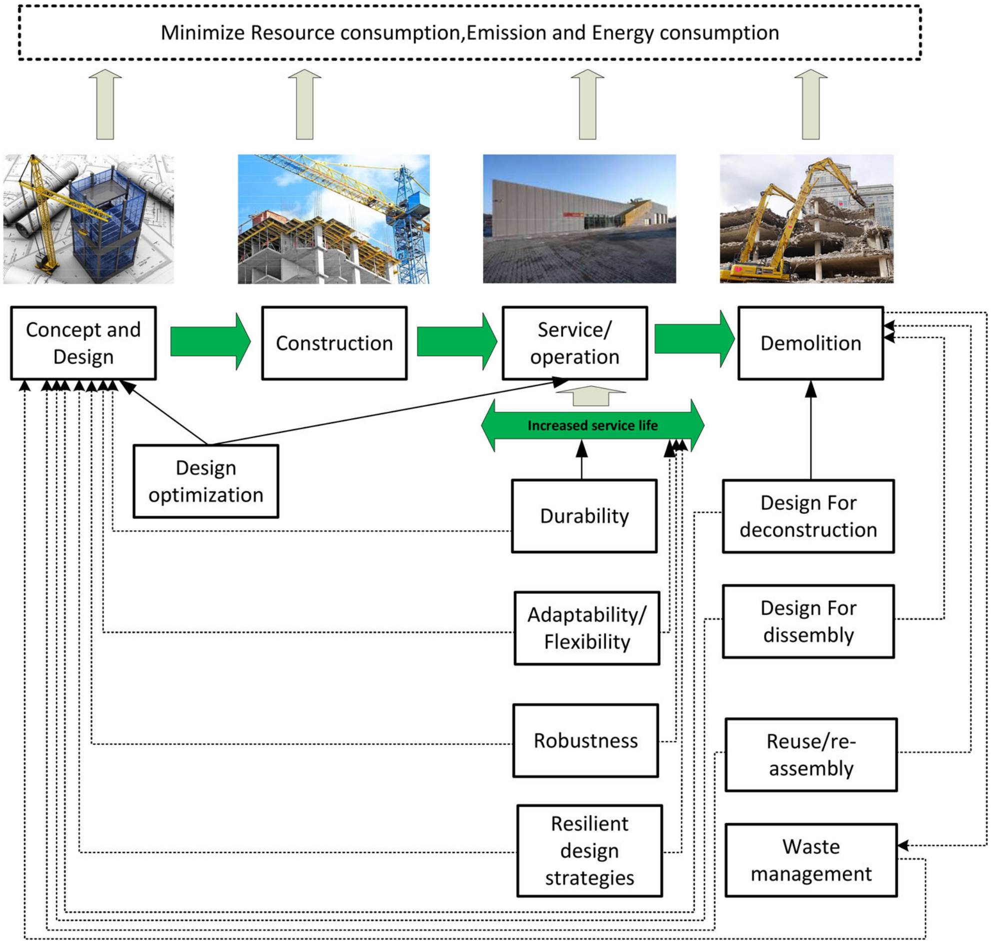

FIGURE 1 The main phases in the life of a physical asset and implementation of CE (adapted from Gervasio and Dimova[9])

there is a challenge in adopting the CE model due to poor building information management. However, the integration of BIM models is the most appropriate way to overcome the aforementioned challenges.[27] Moreover, BIM capabilities such as clash detections at an early stage, design error reduction, effective collaboration of stakeholders, visualization, simulation of waste performances, and waste management play a significant role in implementing the CE model.[24] In addition, currently, while designing new structures for most large-scale engineering construction projects, BIM deliverables are mandatory, but this is not relevant for small-scale projects. Moreover, material passport (MP) can be one of the BIM deliverables, which consists of information about the materials used in a building/bridge to accomplish circular design.[26] Hence, the utilization of the aforementioned BIM capabilities during new large-scale projects would help to implement the CE model.

It is vital to get a clear understanding about MP and its applicability during the adoption of the CE model.[28] Furthermore, the MP consists of information about the composition of the material, mass of the recyclable and waste material, and environmental impact due to the material.[28] The generation of MPs for different materials used in a structure is a time-consuming task. However, it is possible to use BIM models, and LCA data can be used to efficiently develop such MPs for a building (see Figure 2).

With reference to Figure 2, it is possible to perform LCA by collaborating with BIM models, and the results of LCA are used to develop the MP. In addition, it is possible to group (i.e., use of group technology) the structural/non-structural components into different categories, taking into account the characteristics of the components. According to published research findings, the use of group technology in manufacturing processes helps to both improve the productivity and increase the efficiency of the process.[29] However, there are limited applications of the group technology concept in civil engineering applications. In this case, use of group technology concepts is based on creating families of components with similar characteristics (i.e., building materials, location and condition, etc.) for each component family, and a representative component is designated. In addition, the environmental policy approach of extended producer responsibility (EPR) can contribute to achieve circular economy goals by minimizing waste generation.[30,31] Moreover,

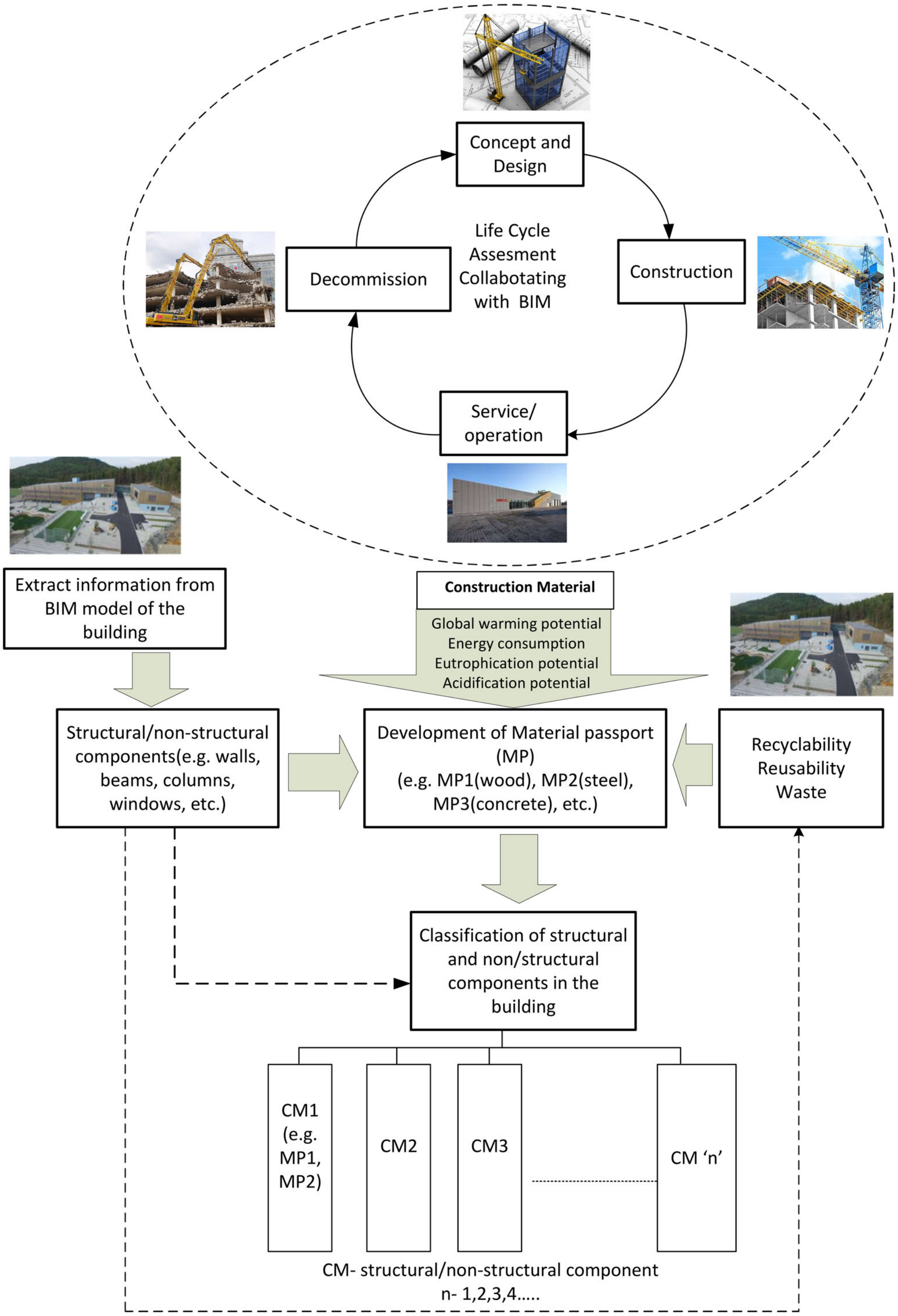

FIGURE 2 An approach to integrate building information modeling (BIM) for the generation of the material passport (MP) and life cycle assessment (LCA)

EPR is able to examine the environmental impact in entire lifecycle of precast concrete products including takeback, recycling, and final disposal.[31] However, the implication of EPR in construction industry is still challenging due the complexity in prefabrication process.

The MP plays a vital role in the decision-making during the selection of materials and the level of circularity of the buildings.[32] The BIM-based MP has different roles at different phases in the life of physical assets.[28] In the concept and design stage, the BIM-based MP serves as an optimization tool, whereby in later stages, it acts as a documentation and inventory of building stocks.[33] For example, when a building is at the end of the life cycle, it is essential to study the possible end-of-life solutions. In this case, the BIM-based MP is helpful to select the most appropriate end-of-life-solution via an iterative assessment. However, decision-making approaches that are currently used for selecting the end-of-life-solution are centered on economic and technical factors, and less attention is paid for environmental and social aspects. In addition, there are few discussions in the published literature on how to use the BIM-based MP for selecting end-of-life-solutions.

2.3 | Selection of different end-of-life solutions for pre-cast concrete structural components

Cast-in-situ, precast, and a combination of the cast-in-situ and precast are the construction practices that are used to build concrete buildings.[8] A pre-cast concrete building is an assemblage of pre-cast concrete components (e.g., walls, beams, slabs, columns, etc.) that are connected to form a frame capable of resisting external loads. The pre-cast concrete industry has contributed to many projects by building part of the building or the complete building using a practical and economical method of construction. A large number of pre-cast concrete buildings have been built in the period between the 1950s[34] and 1980 s of the 20th centuries in Europe.[35] Most of the precast buildings have been designed for a service life of 50 years and are now reaching its end of life. Therefore, it is vital to study the possible end-of-life solutions for each building component that are aligned with the CE targets. According to literature, reuse of pre-cast concrete components,[11] recycling of material in pre-cast concrete components after demolition,[7] repair/strengthening of the pre-cast components[1] and dumping of the pre-cast component[8] are possible end of life solutions for pre-cast concrete buildings. Moreover, the BIM-based MP provides sufficient information about the material used to make the components, which is helpful during the recycling of pre-cast components.

A variety of qualitative and quantitative criteria have to be considered while selecting an end-of-life solution for a particular pre-cast concrete component. This includes the dismantling time,[8] existing experiences on technical issues related to dismantling/repair methods/recycle options, economic issues (e.g., cost for transport, cost for dismantling, and cost for material), emissions,[36] and energy consumptions[37] for different solutions. However, it is quite challenging to prioritize the end-of-life solutions considering both the aforementioned qualitative and quantitative criteria. Therefore, there is a need for multi-criteria analysis (MCA) approaches to prioritize the alternatives by minimizing the inconsistency in the decision-making process. Conventionally, most decision makers simplify the complex problems into a manageable level by using intuitive or heuristic approaches.[38] As a result of these simplifications, there is a risk of losing important information and ignoring the uncertainty. Hence, there is a need to increase the decision makers' awareness and usage of a variety of MCA tools for complex problems without simplifications. Moreover, a framework has been developed to show how to utilize BIM-based MPs and expert knowledge and experiences while using MCA tools to make optimal decisions, as given in Figure 3.

3 | METHOD

The selection of alternative end-of-life solutions for precast concrete buildings requires a decision-making process that consists of multiple quantitative and qualitative criteria. MCA methods have been extensively proposed in literature for different selection problems, such as Andreolli et al.,[18] Samarakoon and Ratnayake,[17] Sánchez-Garrido et al.,[39] and Sobotka and Sagan.[40] This manuscript uses the MCA method called the AHP method, which has been proposed by Saaty in 1990 as a practical method that helps decision makers to handle complex problems with multiple subjective and conflicting criteria. Use of AHP is widely discussed in the literature, and it is a well-established process to rank priorities of alternatives.

The AHP approach consists of several steps. The most important part of the AHP method is the development of the hierarchy structure for the decision problem, which consists of an overall goal, a group of alternatives for reaching the goal, and a group of criteria that relates to the alternatives to the goal.[17,18] The goal is placed at the top of the hierarchy structure, whereas the criteria and sub-criteria, which contribute to the goal, are placed at lower levels and alternatives to be evaluated are at the bottom level.[18] After developing the hierarchy structure, it is necessary to establish priorities. Each node is evaluated against each of its peers in relation to its parent node. These evaluations are referred to as "pairwise comparisons". The pairwise comparisons of the elements at each level of the end-of-life solution prioritization hierarchical model are carried out using either: *Importance*—when comparing goal, criteria, sub-criteria, or alternatives in relation to their relative importance; *Preference*—when comparing the preference alternatives in relation to a goal, criteria, or sub-criteria; *Likelihood*—when comparing uncertain events or scenarios in relation to the probability of their occurrence.[17] When comparing a pair of criteria/sub-criteria/alternatives, a ratio of relative importance, preference, or likelihood of the factors is established.[17] The weights assigned that represent the judgments of the comparisons are arranged in a matrix for further calculations. The weights in the pairwise comparison matrices (PCMs) are composed using the numerical values, as given in Table 1. At the end of the analysis, it is vital to perform a sensitivity analysis to study the

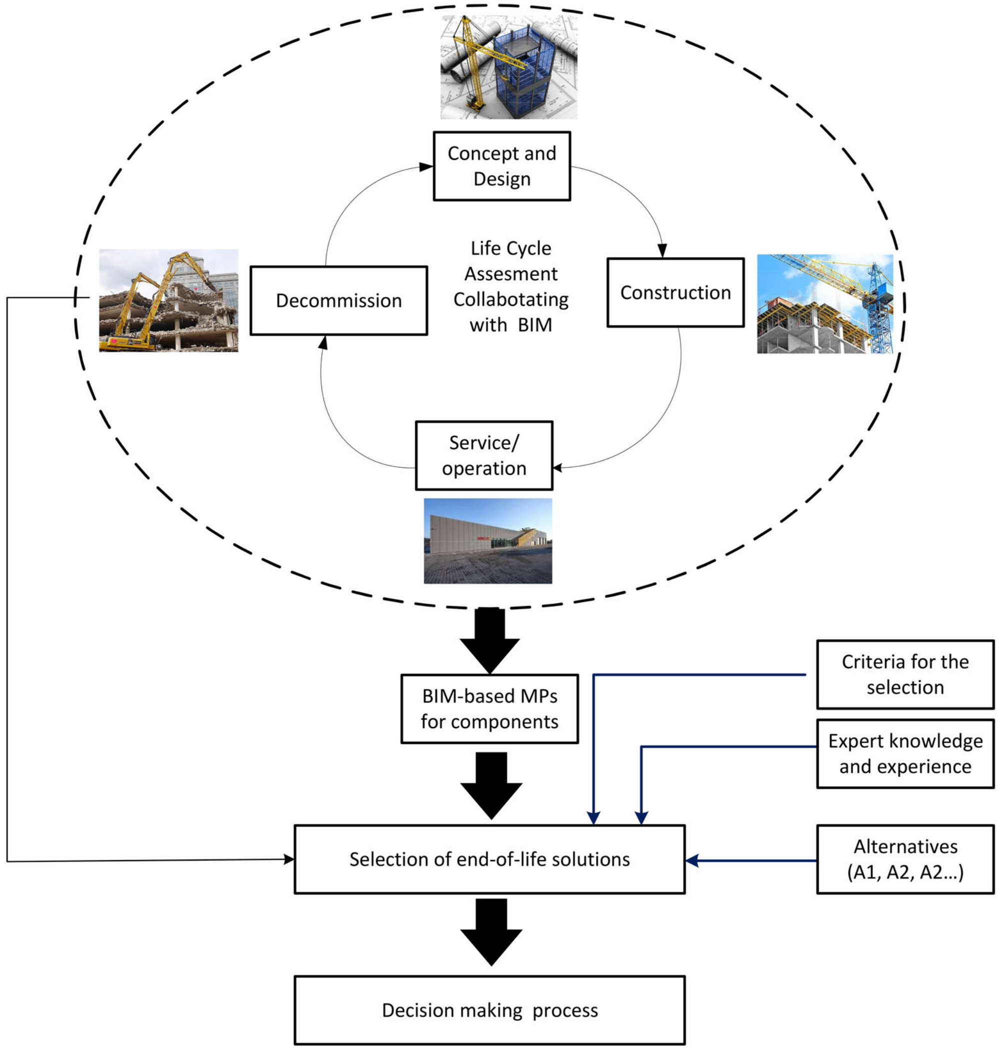

FIGURE 3 Framework to show the utilization of building information modeling (BIM)-based material passports (MP) during the selection of end-of-life solutions

influence of the criteria and sub-criteria on the final ranking and to validate the solution and to test for rank.

Several software packages have been developed by the using mathematical foundation of AHP to carry out prioritization and sensitivity analysis. "ExpertChoice" has been one of the most commonly used decision-making software that uses the mathematical foundation of AHP.[17] In this study, "ExpertChoice" software has been used to prioritize the end-of-life solutions.

3.1 | Selection of the criteria and sub-criteria in relation to the goal

Using the existing literature and expert knowledge, all the important criteria and sub-criteria have been identified while selecting the end-of-life solutions (i.e., goal), as given in Table 2. Existing experience (EE) is one of the criteria that addresses the knowledge of the level of dismantling of different connections,[8] past experience on the usage of different technical solutions,[36] standards/guidelines, and repair/reuse opportunities.[41] Moreover, different levels of dismantling of the pre-cast concrete components are essential to all end-of-life solutions. Therefore, it is vital to plan for dismantling based on the end-of-life solutions, and hence, time taken for dismantling needs to be estimated for use in the AHP analysis.

Total cost (TC) can be considered one of the important criteria that is included in the AHP analysis. TC has been further divided into two sub-criteria, including labor and equipment cost for dismantling (C1), transport cost (C2), and material cost (C3). Moreover, transport cost covers the cost associated with the transport of pre-cast concrete components to a disposal site/recycling plant[36] and/or lifting of the components within the building premises. During the lifting of pre-cast concrete components, O'Grady, Minunno[14] have discussed possible lifting methods for components/material (CM) such as if CM < 20 kg, then one person can lift or if CM < 42 kg, two people can lift, if CM < 50 kg, then hand trolleys can be used, while forklifts for components up to 2000 kg and components heavier than 2000 kg with cranes.[14] The C1 consists of expenses related to tool/machinery/equipment and labor cost required to dismantle the components. C2 covers the material cost for alterative end-of-life solutions.

TABLE 1 Fundamental scale for assessing the importance of activities (pairwise comparison of activities[19])

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

The criteria of energy consumption (EC) address the use of energy for transport of the components and lifting of the components within the building premises. CO_{2eq} emissions (CO) during each end-of-life solution can be estimated by considering the rate of emissions produced by the dismantling activity, share of emissions from scrap resulting from demolition operations, share of emissions from transport off-site (i.e., storage areas, recycling or waste disposal centers), and share of emissions from processing for reuse.[36] The emission level is dependent on the number of tools and machinery required to dismantle structural connections. In addition, to address societal criteria during the selection of end-of-life solutions, safety (S) concerns have been considered. The safety concerns are vital while dismantling, reassembling, and repairing of precast concrete structures.

3.2 | Identification of alternatives: end-of-life solutions for pre-cast concrete components

After carrying out a literature review,[11,12,41–43] four different alternatives have been identified when selecting an optimal end-of-life solution, as given below.

TABLE 2 Descriptions of criteria/sub-criteria

Criterion	Sub-criterion	Description
Dismantling time (DT)		Disconnection of individual parts that make up the fabric of the building, including wall cladding, non-structural wall panels, flooring, kitchens and internal finishes, etc. Pre-cast concrete components are dismantled partially/fully from the existing structure. DT will be time taken for the total operation
Existing experiences (EE)		Existing capability/experience refers to the capability and experience of an entity related to technical issues, for example, what equipment is used for dismantling, knowledge about reuse/recycle, repair options.
Total cost (C)	Labor and equipment cost for dismantling and reassembling (C1)	Cost for labor and equipment/tools required to dismantle and reassemble components: tools (e.g., screwdrivers, spanners), power tools (e.g., drill, angle grinder, impact gun), gas or pneumatic tools (e.g., air operated demolition breakers), and hydraulic equipment (e.g., excavator) Cost for temporary storage of precast concrete components
	Transport cost (C2)	Transport of pre-cast concrete components and necessary equipment/ machinery/ scaffoldings to dismantle
	Material cost (C3)	Cost for material used during repair/reuse/demolition/dismantling
Energy consumption (EC)		Electricity use for machines/equipment/vehicles for removal of connections, transport of components, and lifting of components
CO_2 emission (CO)		Emission from machines/equipment/vehicles during the removal of connections, lifting of components, and transport of the components
Safety (S)		Safety regarding dismantling, reassembling and/or repairing of the precast structural concrete component.

3.2.1 | A1: reuse of pre-cast concrete components

A large amount of waste is generated in the construction industry after disassembling pre-cast concrete buildings. One of the end-of-life solutions for such waste is direct reuse of pre-cast components obtained during the disassembly of the buildings. Various researchers have discussed examples of cases of reuse of pre-cast components.[11,12] The technical condition of an individual pre-cast component is evaluated before recommending it for reuse as a unit/module or as a component.[12] The capacity of the pre-cast concrete walls is estimated, and the durability of the component is examined using destructive or non-destructive testing.

3.2.2 | A2: recycling of the material in pre-cast concrete components

Normally, pre-cast concrete components have been made up using concrete and steel reinforcement. After demolition, the pre-cast concrete components and the aggregate can be recovered. The recycling of a wide variety of industrial waste and its potential use as an aggregate have been discussed in the literature. Over the last few years, extensive research and development activities have been carried out to find the potential replacement of natural aggregates with recycled aggregates in concrete. For example, the recycled aggregate from CDW[41,43] performed well according to the literature. The recycled aggregate can be used as a material for new structural/non-structural components or a subgrade of the new roads and highways.

3.2.3 | A3: repair and life extension of pre-cast concrete components

In this manuscript, the repair of pre-cast components is considered an end-of-life solution for pre-cast concrete components. The repair of pre-cast components can be defined as the repair and maintenance of defective or partially damaged components in such a way that they can perform their original function. The assessment of the condition using analytical tools and visual, field, and laboratory experiments for core samples collected from the components is essential prior to repairing the components. After repairing the components, owners can determine whether a component is fit for its intended purpose. Moreover, the strengthening of structures is a current topic of interest to society because it is in line with the circular economy and the environmental guidelines. Hence, the life of the components can be extended. However, currently, the construction industry is facing challenges during the selection of repair materials to restore the strength and serviceability of the structure by considering the shape and amount of damage, construction cost, time, and practicality.[42] In addition, there is a possibility to repair or strengthen precast components on building site without the need of elements to be de-assembled and transported somewhere else.

3.2.4 | A4: disposal of pre-cast concrete components/material into the landfill

The dumping of pre-cast concrete components/materials into the landfill can also be considered as an end-of-life-solution. Generally, in Europe, 20%–30% of the total waste is generated from CDW.[44] CDW waste consists of wood products, asphalt, drywall, concrete, and masonry. Moreover, CDW waste volumes have been increasing, resulting in a shortage of landfills and long-term adverse environmental, economic, and social impacts.

4 | ILLUSTRATIVE EXAMPLE

The existing pre-cast buildings consist of different structural and non-structural components. Therefore, it is vital to consider possible end-of-life alternatives for both types of components to make a right decision to support circular economy initiatives. Both qualitative and quantitative criteria are taken into account to prioritize the end-of-life solutions. The illustrative example shows how to use AHP to select an end-of-life solution. Figure 4 shows the AHP decision hierarchy developed to make a decision on the end-of-life solution for a pre-cast concrete wall. The criteria and sub-criteria in relation to the goal were chosen as discussed in Section 3.1. According to literature, EE can be considered as a criterion that consider the knowledge of the level of dismantling of different connections in precast walls, experience on the usage of different technical solutions for walls, standards/guidelines, and repair/reuse opportunities. Based on the expert knowledge, total cost (TC) can be considered one of the important criteria in relation to the goal for a precast concrete wall. The criteria of energy consumption (EC) address the use of energy for transport and lifting of the concrete wall. According to literature,[36] CO_{2eq} emissions (CO) was considered as a criterion considering the rate of emissions produced by the dismantling activity, share of emissions from scrap resulting from demolition operations. TC criterion was divided into sub-criterion as labor

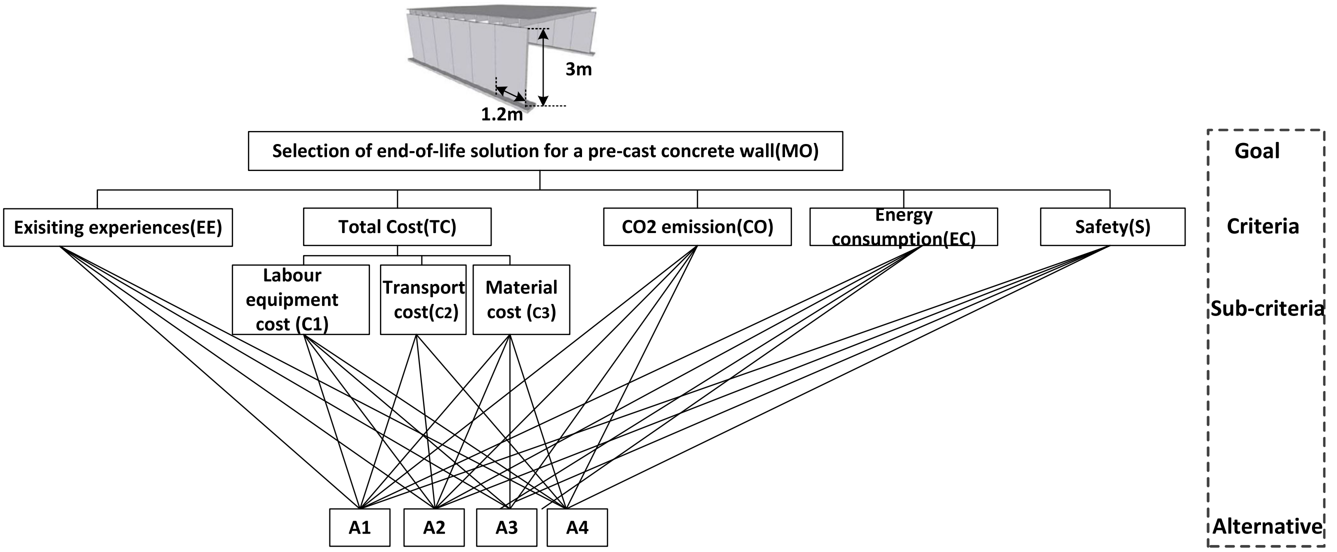

FIGURE 4 Analytic hierarchy process structure for a pre-cast concrete wall

TABLE 3 Example values for a pre-cast concrete wall panel (height: 3 m, width: 1.2 m, thickness: 150 mm)

Main criterion	Sub-criterion	Alternative 1 (A1)	Alternative 2 (A2)	Alternative 3 (A3)	Alternative 4 (A4)
Existing experiences (EE)		Low (30%)	High (70%)	Medium (50%)	Very high (90%)
Total cost (TC)	Labor and equipment cost for dismantling (C1)	\$853	\$400	\$450	\$310
	Transport cost (C2)	\$1000	\$1300	\$1100	\$1200
	Material cost (C3)	\$75	\$20	\$100	\$50
Energy consumption (EC)		8 MJ	10 MJ	7 MJ	15 MJ
CO_2 emission (CO)		36 kg CO_{2-e}	106 kg CO_{2-e}	20 kg CO_{2-e}	60 kg CO_{2-e}
Safety (S)		High (100%)	Medium (50%)	Medium (50%)	Low (25%)

and equipment cost for dismantling (C1), transport cost (C2), and material cost (C3).

Table 3 shows the estimated qualitative and quantitative values for each criterion and sub-criteria involved in the decision-making process. The estimated values are based on expert knowledge and using information given in literature and web page companies. To discuss the EE of different alternatives, a qualitative scale of "Very high, High, Medium, Low, and Very low" has been used. Similarly, the qualitative scale can be represented quantitatively using the scale of 0–100. In addition, TC can be further divided into three main mutually exclusive cost categories as labor and equipment cost for dismantling (C1), transport cost (C2), and material cost (C3). C1 consists of expenses associated with skilled or non-skilled-labor and equipment/tools used for dismantling. However, there are limited studies on the dismantling time of existing pre-cast concrete walls to estimate C1. Moreover, the dismantling time will be different from one end-of-life solution to the other due to the required level of dismantling. Based on the distance to the landfill site, recycling plant, and the new building site where the component is reused, C2 can be estimated. In addition, each alternative requires different equipment/tools/lifting mechanisms based on the activities taking place. As a result of that, the cost figures may be different from one alternative to another alternative. Moreover, in this illustrative example, the CO_2 emission during the transport of pre-cast concrete components has been estimated using the values for outbound: 0.133 kg $CO_{2-e}/m^3/km$ and return: 0.098 kg $CO_{2-e}/m^3/km$.[37] The energy consumption during the transport of a pre-cast wall is estimated based on outbound: 1.903 and return: 1.404 $MJ/m^3/km$.[37]

To evaluate safety concern for different alternatives, a qualitative scale of "High (the risk of potential failure is very low), Medium, and low (the risk of potential failure is very high)" has been used. Similarly, the qualitative scale has been represented quantitatively using the scale of 0–100.

It is vital to carry out a pair-wise comparison of the criteria in relation to "Goal", as given in the matrix in Figure 5. The fundamental scale given in Table 1 can be used. For example (see Figure 5a), EE is 5 strongly important (contribute to dominate, influence, satisfy, or benefit) than TC in relation to Goal. Moreover, a pair-wise comparison of the alternatives in relation to each criterion and sub-criteria should be carried out. Figure 5b shows how to compare two alternatives in relation to CO. To estimate the relative importance while comparing two alternatives, the CO values given in Table 3 have been used. For example, A1 is 2.94 (106 kg CO_{2-e}/36 kg CO_{2-e}) times more favorable compared with A2 in relation to CO (A1 gives less CO_2 emission compared with A2). A similar analysis is carried out for EC and TC.

$$\begin{array}{c} \\ EE \\ TC \\ CO \\ EC \\ S \end{array} \begin{array}{c} \begin{array}{ccccc} EE & TC & CO & EC & S \end{array} \\ \begin{bmatrix} 1 & 1 & \frac{1}{5} & \frac{1}{4} & \frac{1}{3} \\ 1 & 1 & \frac{1}{3} & \frac{1}{5} & \frac{1}{2} \\ 5 & 3 & 1 & 1 & 1 \\ 4 & 5 & 1 & 1 & 1 \\ 3 & 2 & 1 & 1 & 1 \end{bmatrix} \end{array}$$

(a)

$$\begin{array}{c} \\ A1 \\ A2 \\ A3 \\ A4 \end{array} \begin{array}{c} \begin{array}{cccc} A1 & A2 & A3 & A4 \end{array} \\ \begin{bmatrix} 1 & 2.9 & \frac{1}{1.8} & 1.7 \\ \frac{1}{2.94} & 1 & \frac{1}{5.3} & \frac{1}{1.8} \\ 1.8 & 5.3 & 1 & 3 \\ \frac{1}{1.7} & 1.8 & \frac{1}{3} & 1 \end{bmatrix} \end{array}$$

(b)

FIGURE 5 (a) Matrix to compare two criteria in relation to "goal". (b) Matrix to compare alternatives (i.e., A1, A2, A3, and A4) in relation to CO

5 | RESULTS OF THE ANALYSIS

The ExpertChoice software has been utilized for estimating priorities, as discussed in Section 3, and carrying out the sensitivity analysis. ExpertChoice.com references over 1000 articles and doctoral dissertations using AHP.[45] The "pairwise graphical comparison" option, which is available in the "ExpertChoice" software, has been used to insert the values. The results have been obtained, as shown in Figure 6. According to the analysis, the repair and life extension constitute the optimal solution. The final selection is consistent, as the overall inconsistency is <0.01. Figure 6 also indicates the synthesis with respect to the goal—the selection of the optimal end-of-life solution alternative on the right "y-axis". Furthermore, it illustrates how the alternatives have been prioritized relative to other alternatives with respect to each criterion as well as overall. The best alternative end-of-life solutions compared to the others have been illustrated by the overall priority from the intersection of the right "y-axis". It presents the overall priority for each alternative. For instance, in this case, A3 is ~0.323 (i.e., considered to be the optimal selection with the highest weight), A1 is ~0.307, A2 is ~0.201, and A4 is ~0.169 (note that the priorities for the alternatives sum to one) (see right "y-axis" in Figure 6). The left "y-axis" in Figure 6 illustrates each criterion priority (based on the engineering expert's paired comparisons). For instance, EE is about 7.4%, TC is about 8.6%, CO is about 28.9%, EC is about 30.8%, and S is about 24.3%.

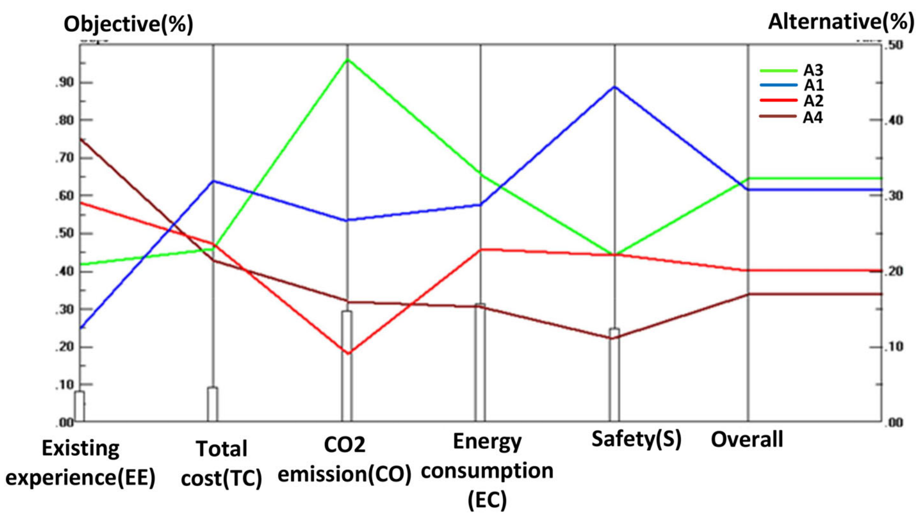

FIGURE 6 Performance sensitivity (goal: selection of an alternative end-of-life solution)

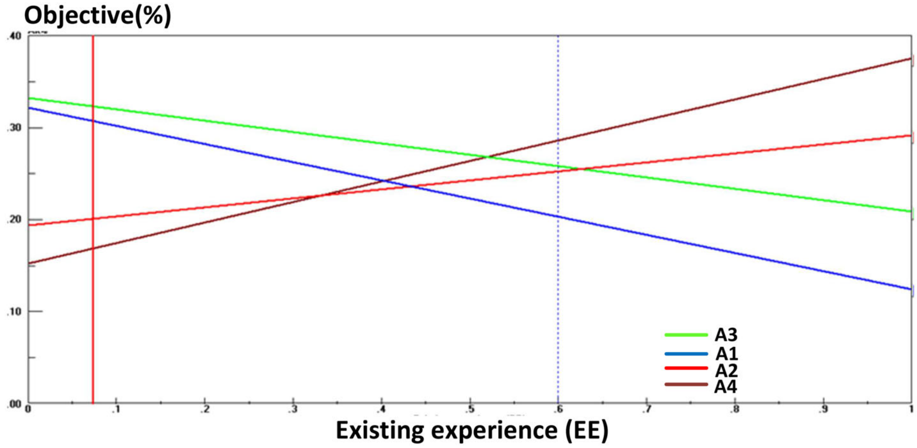

FIGURE 7 Gradient sensitivity (goal: selection of an alternative end-of-life solution)

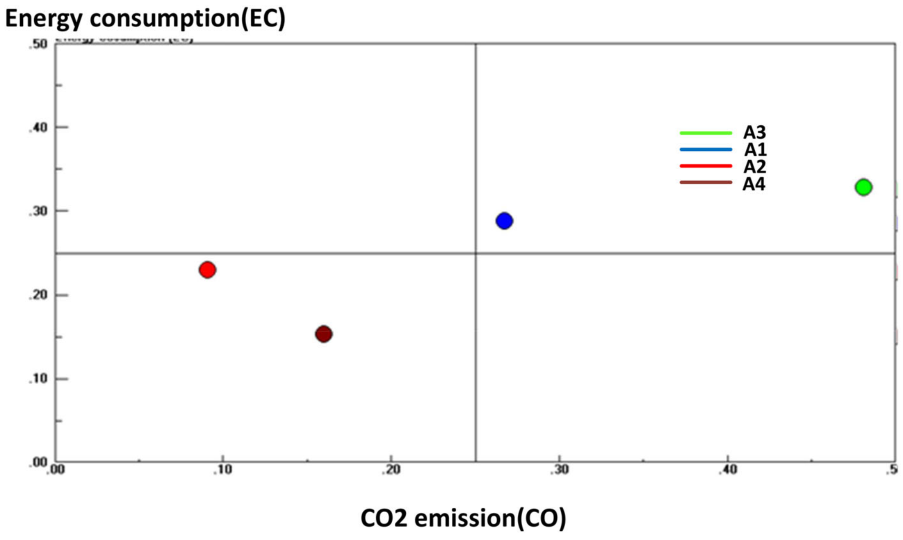

FIGURE 8 Two-dimensional sensitivity (goal: selection of an alternative end-of-life solution)

The gradient sensitivity analysis results demonstrate the influence of the priorities of the alternatives with respect to one criterion at a time. Figure 7 shows a gradient sensitivity analysis of the influence of the priorities of the alternatives with respect to EE. According to Figure 7, the red vertical line indicates the criterion's priority (based on the decision maker's paired comparisons). Changing the position of the red line to the left or right, it is possible to indicate how a criterion's priority changes. For instance, this is indicated as a blue dashed vertical line where EE has changed to 0.60. Once EE has changed to 0.6, then the priority of the alternatives has changed as A4, A3, A2, and A1, respectively. Such analysis supports making a logical trade-off between different alternatives instead of moving to ad hoc conclusions.

Two-dimensional sensitivity analyses for nodes have been carried out to show the priorities of the alternatives with respect to two criteria at a time. For example, Figure 8 shows two-dimensional sensitivities for energy consumption (EC) versus CO_2 emission (CO). Essentially, here, the area of the two-dimensional plot is divided into quadrants. The most favorable alternatives with respect to the criteria on the two axes are those in the upper right quadrant (i.e., the closer to the upper right corner, the better the alternative). The least favorable alternatives are shown in the lower left quadrant (i.e., the closer to the lower left corner, the less favorable the alternative). If alternatives are located in the upper left and lower right quadrants, then they indicate key trade-offs where there is a conflict between the two selected criteria.

6 | CONCLUSIONS

The utilization of BIM capabilities and MP during new large-scale projects would help to implement the CE targets. A framework has been developed to show how to utilize BIM-based MPs and expert knowledge and experiences while using MCA tools to make optimal decisions.

The selection of the optimal end-of-life solution is a challenge among engineering experts due to the lack of extensive knowledge about MCA approaches. The use of MCA techniques helps while dealing with complex problems by imposing a structure that directs attention to the criteria in proportion to the weight they deserve. There are different methods such as performance matrixes, scoring and weighting, multi-attribute utility theory, fuzzy set theory, linear additive models (i.e., AHP), and outranking methods utilized for MCA. The linear additive methods such as AHP have been used in this study. The decision model in AHP is mathematically rigorous and operationally simple and transparent where the analysis results are based on the experts' judgments. Moreover, the advantages of AHP are the ability to assess the inconsistencies in decisions, flexibility, intuitive appeal to the analysts, possibility of decomposing a decision problem into its constituent parts, ability to build hierarchies of criteria, capability to capture both subjective and objective evaluation measures, support of group decision making, and ability to assess model situations of uncertainty and risk.[17] This manuscript illustrates the use of AHP for making decisions on an optimal end-of-life solution and possible sensitivity analysis, evaluating possible trade-offs. The overall synthesis delivers the priorities of the end-of-life solutions based on the pairwise comparisons. Apart from that, performance, gradient, and two-dimensional sensitivity analyses provide alternative means to study how the final selection has been made. Moreover, the performance sensitivity analysis gives the indication of priority changes due to the changes in the experts' judgments. This enables one to see how different criteria and sub-criteria contributed to the final priorities. Hence, the suggested approach provides transparency in selecting the end-of-life solutions in relation to the criteria and sub-criteria. However, the drawbacks, such as "ranking irregularities", "need of decomposing MCA problem into a number of subsystems", and "requirement of performing substantial number of comparisons within which and between which", limit the use of AHP. Also, the aforementioned approach has the limitation regarding the number of pairwise comparisons to be made (i.e., the number of comparisons shall become very large $[n(n-1)/2]$, while modeling and analysis shall become a lengthy task).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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