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Review

Life Cycle Cost in Circular Economy of Buildings by Applying Building Information Modeling (BIM): A State of the Art

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Abstract: The building industry is one of the largest consumers of materials resources and significant contributors to global waste. Applying core principles of circular economy (CE) could significantly help the environment by reducing waste and decreasing the life cycle cost of buildings. Several strategies to implement the concept of CE in buildings include design for deconstruction, adaptability, and flexibility. However, implementing these design strategies could face constraints. In this study, we identified 22 barriers related to the adoption of CE in buildings, as reported in the literature. We discussed the role of Building Information Modeling (BIM) in overcoming those barriers. This paper demonstrates how BIM can facilitate the implementation of CE principles while providing critical insights into the life cycle costs of circular buildings. We identified 14 ways to use BIM to foster the implementation of a circular economy approach. To achieve these objectives, we have undertaken a thorough review of recent publications that explore CE design strategies, Life Cycle Costing in the circular construction of buildings, and BIM developments in the building industry. This literature review is based on 88 articles covering BIM's role in enhancing the management of a building's end-of-life while reducing the life cycle cost in the circular construction of buildings.

Keywords: circular economy; LCC; BIM; CE; barriers; buildings; life cycle cost

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1. Introduction

Most of the world's population lives in cities [1], whose most prominent component is buildings. Hence, the development of the building sector is crucial for both social welfare and economic growth. The counter side is that economic development has significantly harmed the environment, with the building sector carrying 33% of greenhouse gas emissions, 40% of resource use, and 40% of waste production [2], with only 20–30% of such resources being recycled or reused at the end-of-life [3]. Therefore, reducing the environmental impact associated with construction is an unavoidable necessity.

Strategies to attain the goal of sustainable construction include the use of eco-friendly materials with low carbon emissions and reused/recycled materials. The list expands to increasing the share of renewable resources, reducing materials loss, eliminating waste, renovating, or preserving old building stocks, and identifying more resilient and energy-efficient materials. Researchers have realised that all those strategies converge to the broader concept of circular economy [4].

Circular economy (CE) is "An industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" [4]. In a circular economy approach, building components are kept in a loop involving use, reuse, repair, and recycling, allowing resources to retain their highest intrinsic value for as long as possible [5]. As a result, waste is eliminated, and CO_2 emissions are prevented [3]. Furthermore, the CE model can create economic growth and reduce environmental impacts [6].

Designing for adaptability, flexibility, disassembly, and deconstruction are various strategies for implementing a circular economy to allow building components to be dismantled and replaced or repaired [7]. Akanbi et al. [8] pointed out that designing for deconstruction would preserve embodied energy and reduce carbon emission, pollution, and cost. Munaro et al. [7] added that a construction project designed for adaptability and deconstruction adds flexibility in using physical space and recovering end-of-life components.

Barriers associated with implementing circular economy strategies in buildings [5,9,10] derive from the lack of understanding, experience, and skills in the implementation of the principles of the circular economy [11–15], which add to the lack of fiscal incentives to design buildings and products for deconstruction and reuse at their end-of-life [13,16–22]. Tirado et al. [23] highlighted that selective deconstruction can be achieved successfully through more robust planning stages, accompanied by the willingness and capability of stakeholders to adopt these strategies. According to Chini and Balachandran [24], less than 1% of buildings are demountable. Instead, buildings are traditionally built to be demolished at the end of their useful life rather than deconstructed or adapted [5,12,14,15,25,26]. Technical barriers that often hamper CE strategies include building complexity [11,13,16], lack of building data management, and knowledge of the quality and quantities of reclaimed materials [27–29].

Circular economy strategies can reduce buildings' life cycle costs (LCC) [30]. Slaugter [31] stated that the cost and time for flexible buildings are reduced by 2% of the initial construction cost within the first renovation. In contrast, Manewa et al. [32] asserted that adaptable buildings reduce the life cycle cost, especially in maintenance and operations. Notwithstanding, CE strategies are being impeded by several barriers. Amongst those, the higher cost associated with circular design strategies and the lack of people understanding the benefit of circular design strategies within the life cycle cost, as stated by Rios et al. [12]. According to Charef et al. [29], these challenges could be overcome by digitising building materials and components. However, Charef et al. [29] also asserted that there is a scarcity of studies that promote BIM for integrating circular economy principles throughout the building life cycle. Those findings were confirmed by Chong et al. [33], who conducted a study to review the adoption of BIM for sustainability and revealed that academic publications on how BIM can be applied in the refurbishment and demolition process are rather limited.

BIM facilitates accurate cost estimation, minimizes unforeseen expenses, and improves cost control [34]. These outcomes enable designers to receive real-time decision support data and help develop BIM for sustainability purposes, significantly reducing the time, errors, and effort associated with LCA and LCC [35]. Through BIM, a virtual representation of the building is created. This makes visualizing, coordinating, and analysing the project more manageable, leading to a more accurate cost estimate. As a result of this information, stakeholders can make informed decisions regarding budget allocations and resource utilisation, reducing overrun risk.

Zoghi and Kim [36] stated that BIM platforms can enhance LCC results consistency and accuracy. Additionally, the researchers examined the use of BIM to minimise construction waste and building sustainability. Furthermore, BIM facilitates efficient facility management and helps reduce long-term costs. Material specifications, maintenance schedules, and equipment data are all included in the detailed database created by BIM. As a result, facilities management is made more effective. Providing access to information regarding maintenance needs, replacement schedules, and energy efficiency can assist facility managers in planning and allocating resources more efficiently, reducing long-term operational costs.

This paper aims to fill the lack of articles on BIM-enabled LCC analysis integrated with the circular economy. Although separate studies have examined BIM, LCC analysis, and circular economy, a comprehensive examination of how these aspects are integrated is lacking. This paper aims to fill the gaps identified by examining the potential of BIM in overcoming circular building construction barriers while helping to reduce LCC in constructing buildings via a circular economy. This study contributes to understanding how BIM can support sustainable construction practices and promote the construction industry's transition to the circular economy.

2. Methods

This study aims to conduct a comprehensive literature review to identify circular economy strategies for enhancing the life cycle cost of circular construction buildings through BIM. The search used three academic databases to achieve this objective: Scopus, Web of Science, and Google Scholar.

Two stages were used to evaluate the articles in the search strategy literature review. The SPIDER tool (Sample, Phenomenon of Interest, Design, Evaluation, Research type) framework and the Critical Evaluation of Article (CEA) checklists were used to conduct this literature review. As part of the first stage of the review process, the SPIDER was implemented as a tool to delineate critical elements of the review question and as a means of standardising the search process:

1. *Sample:* This review focused on studies involving BIM and LCC within the context of the Circular Economy. This sample search employed keywords used the following terms: "Building Information Modelling", "Life Cycle Cost", "Circular Economy", OR "BIM", "LCC", and "CE", specifically in the context of Civil engineering. The study considered articles published in English from 2013 to 2023.
2. *The phenomenon of Interest:* This study examines how BIM can be utilised to manage LCC within the circular economy. This search used the following terms: "Building Information Modelling", "Life Cycle Cost", "Circular Economy" OR "BIM", "LCC", "CE" OR "circular buildings" OR "circular construction" OR "circularity", and combinations of phrases such as "BIM enhances LCC in the circular economy of buildings".
3. *Design:* A qualitative and quantitative study design was considered to grasp the current scope of the topic fully.
4. *Evaluation:* It includes studies that assess and evaluate the effects of BIM on life cycle costs in circular economy contexts, such as managing the end-of-life of buildings while reducing their life cycle costs.
5. *Research type:* Case studies, experimental studies, mixed methods, and theoretical discussions are among the types of research covered in this review.

Initially, search results were imported into an Excel spreadsheet, and duplicates were removed. Full-text access to potentially relevant studies was conducted, and titles and abstracts were screened for eligibility. The search criteria include and exclude papers whose scopes do not relate to the research topic and whose analyses do not relate to CE, BIM, or LCC. Based on these assessments, it was then decided whether the paper should be accepted or rejected.

In the second stage of the review process, CEA checklists were used to assess whether papers should be accepted or rejected. As part of CEA checklists, prompt questions were used to evaluate the articles to determine if they are relevant to the criteria laid out for review and which articles should be highlighted. As part of reviewing a paper that has been accepted for review, the following questions have been considered:

1. Does the article relate to the topic?
2. Was the article focused on BIM, LCC, or CE?
3. Does the study design of the paper match the purpose of the paper?
4. Is the article relevant to the review's objectives?
5. Is there a clear contribution to the field of knowledge in this article?

As a result of the CEA Checklists, a study's reliability, design, and methodology can be ensured, and the research findings can be trusted. The checklists help determine whether the study's results can be relied upon, what they are, and if they apply to a topic context. Using the SPIDER tool and CEA Checklists, numerous results were generated, which were then filtered based on relevance. Additional criteria were used to refine the selection, such as excluding duplicate articles, non-English publications, and articles that did not explicitly address the research topic. A comprehensive full-text evaluation of the remaining articles was conducted to assess their quality and relevance. A critical inspection of the abstracts of 88 shortlisted articles was performed to ensure that the articles were aligned with the research topic.

The study identified key articles and extracted relevant information during the metadata extraction phase. This process involved the assessment of the articles concerning the keywords, as these keywords assist in guiding citations and article recommendations. This finding suggests the need for further research in this area to promote circular economy principles by using BIM. Figure 1 demonstrates the methodology process.

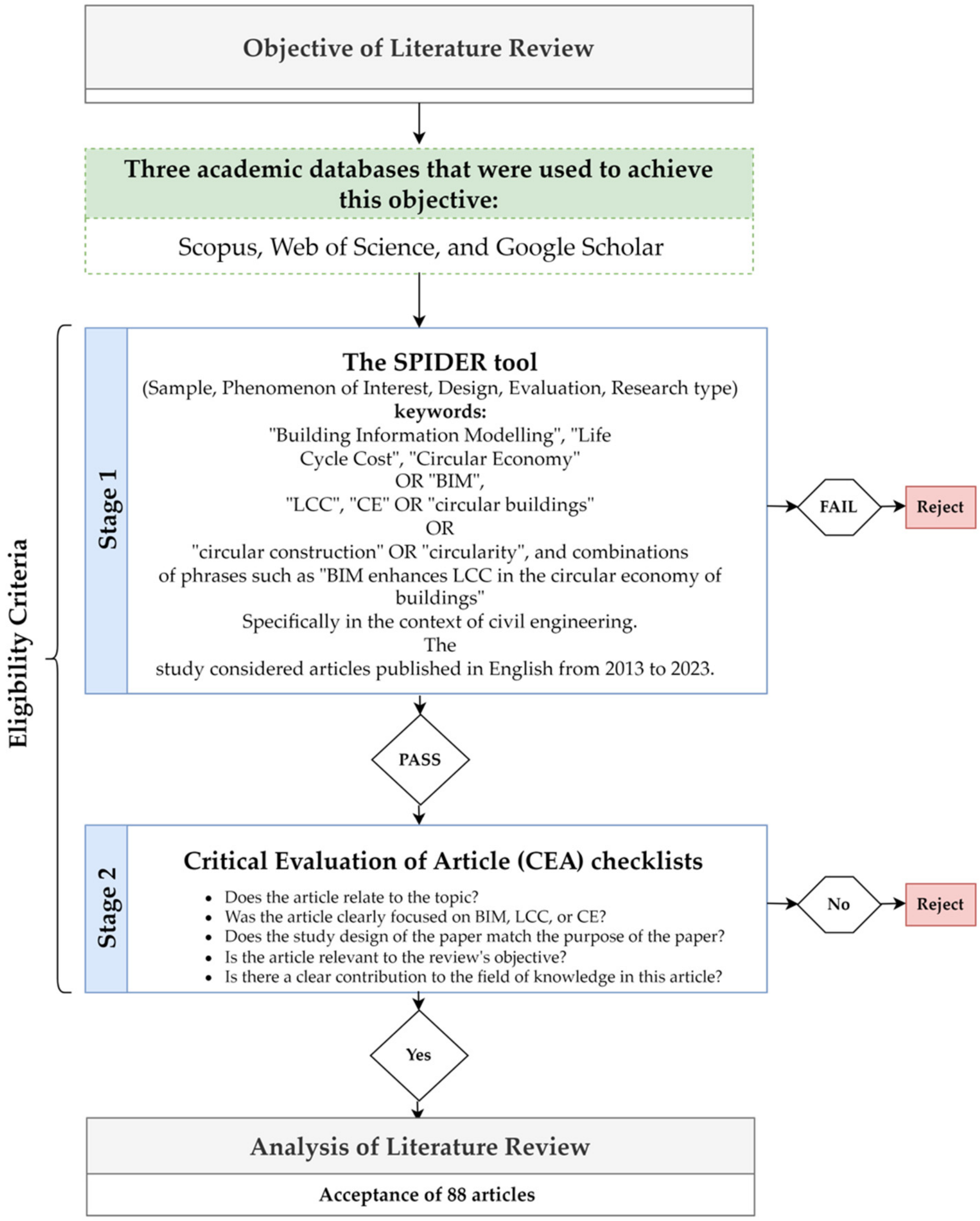

Figure 1. Methodology to flag scientific research.

3. Results and Discussions

3.1. Circularity in Building Construction

The circular economy is a regenerative system that reduces waste and emissions by implementing durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling materials and components [37]. Similarly, Akerman et al. [38] explained the term CE as "an economy that runs materials cycles as closed as possible, ultimately resulting in de-coupling material consumption and economic growth". Stahel [6] highlighted the benefit of the CE and claimed that CE was the ultimate low-carbon economy. A circular building accommodates remodelling, disassembly, and expansion to help overcome current environmental issues [39].

According to Kubbinga et al. [40], a circular building can be defined as "A building that is developed, used, and reused without unnecessary resource depletion, environmental pollution, and ecosystem degradation. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, no, and later. Technical elements are demountable and reusable, and biological elements can be brought back into the biological cycle".

In addition, Pomponi and Moncaster [41] defined the term circular building as "a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles ". Leising et al. [42] defined the CE approach for circular buildings as "a life-cycle approach that optimises the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank".

The lifetime of a circular building should be a closed-loop system in which components and materials are used and retained appropriately [25]. To effectively implement CE, carefully selecting materials with low embodied carbon and energy is essential. These materials should also possess high quality and can accommodate reversibility while maintaining optimal building performance and user comfort [5]. Implementing a CE approach in buildings involves a series of stages for building materials. This includes the initial construction, utilisation during the building's lifespan, subsequent deconstruction or dismantling, potential reuse, or recycling of materials, and ultimately return to the loop of resources available for future construction purposes [43].

Rahla et al. [44] conducted a review study to determine the technical criteria of building components and materials adopted in the literature under CE principles. The nine criteria are: (Upcycling potential, Recycled and recovered content, Maintainability Recyclability, Energy recoverability, Reusability, Ease of Deconstruction, Durability, and Biodegradability).

3.2. Circular Economy Design Strategies

Designing buildings under the principles of CE significantly emphasises the end-of-life phase of the building's materials and components [45]. Multiple design strategies exist in the literature to aid with implementing CE. Design for disassembly (DfD) is one of the key strategies for implementing CE in buildings [13,26,46,47]. Thormark [48] defined design for disassembly as a design method used in buildings to ensure that building components can be easily disassembled at the end of their useful life and its parts can be reused or recycled with minimal waste. Modularity and prefabrication are interlinked concepts in facilitating DfD [49]. DfD has the potential to mitigate environmental impacts and minimise waste generation associated with building demolition [14,50]. However, according to Akinade et al. [8], the successful adoption of DfD strategies in real-world cases lacks substantial evidence due to the considerable uncertainty associated with the long lifespan of buildings [13,15,51]. Rahla et al. [25] stated that materials in design for disassembly should be compatible with CE standards such as reuse, refurbishment, and repair and should be of greater purity to prevent quality loss throughout the assembly/disassembly process.

Even though the design for deconstruction/disassembly is not widely adopted in the building sector [7,52], multiple studies have identified strategies to facilitate deconstruction in buildings. Crowther [53] listed 27 design principles for disassembly that could become design guidelines or techniques to overcome design challenges. Tingley and Davison [54] highlighted 33 strategies for deconstruction design through a comprehensive literature review. Buyle et al. [55] conducted a study to measure the potential impact on the environment of introducing circular design options for internal wall assemblies through consequential life cycle analysis. Hartwell et al. [56] developed a disassembly evaluation framework to assess the viability of reclaiming materials from façade systems.

Designing for adaptability (DfA) and flexibility is another effective strategy for implementing CE in buildings [57,58]. Schmidt et al. [59] defined design for adaptability as “a design characteristic embodies spatial, structural, and service strategies which allow the physical artefact a level of malleability in response to changing operational parameters over time”. Addis and Schouten [60] emphasised design principles for flexibility and adaptability. They defined an adaptable building as “a building that has been designed, constructed and maintained with the thought of how it might be easily altered to prolong its life”. In contrast, a flexible building is “a building that has been designed to allow easy rearrangement of its internal fit out and arrangement to suit the changing needs of occupants”. Adaptable buildings should prioritise manageability, adaptability, simplicity in design, and upgradability to satisfy user wishes while minimising quality loss and environmental implications [25]. McFarland et al. [61] added that adaptable buildings contribute to a circular built environment by extending buildings’ life and reducing waste.

Design for Adaptability and Disassembly (DfAD) is an inclusive CE design strategy which combines the benefits of DfD and DfA that allow building components to be disassembled for reuse/recycle and buildings layers to be adopted for any required changes [7]. Although only three studies [62–64] mentioned the DfAD method, the term has been embraced as a positive contribution to sustainable development in construction by the Standards Council of Canada and the International Organisation for Standardisation (ISO) 20,887 [7]. Webster [63] asserted that DfAD is the most effective strategy for material conservation as it increases the probability of extending the building’s useful life, enabling its components and materials to be reused/recycled. To raise awareness and promote implementing the DfAD concept within the construction sector, Munaro et al. [7] developed a conceptual framework for implementing DfAD throughout the building life cycle. Figure 2 shows different CE design strategies.

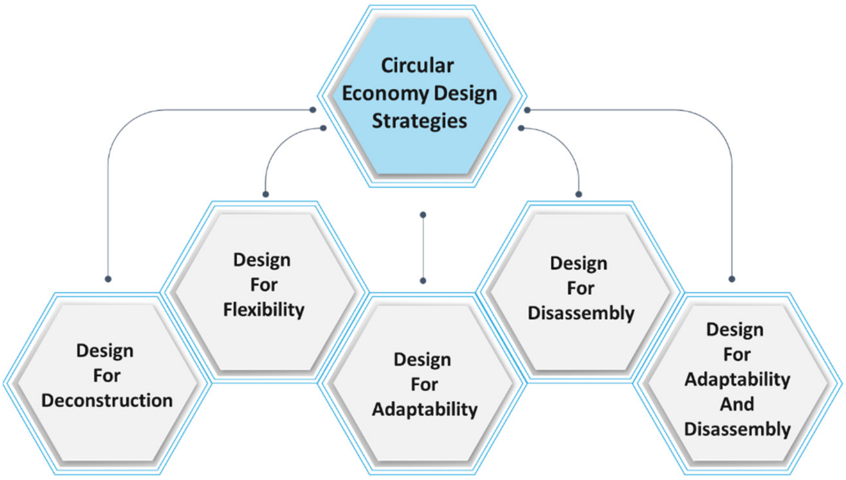

Figure 2. Circular economy design strategies.

3.3. BIM as an Enabler for Promoting Circular Economy

Promoting the CE has become a critical policy objective in the European Union and beyond [38]. BIM is a powerful tool that has the potential to promote circularity in buildings through materials selection, waste minimisation, energy-saving alternatives, cost estimations, and enhancing communication between stakeholders [65]. Minunno et al. [66] added that the future disassembly of buildings can be effectively planned with BIM. According to the National Institute of Building Sciences (NIBS) [67], BIM is defined as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward".

Moreover, BIM represents a virtual model that integrates all disciplines and systems of a facility into a unified model, enabling enhanced accuracy and efficiency in collaboration among all design team members [68]. BIM virtual environment provides spatial information, building properties, cost estimations, geometric and geographical information, inventory management, and schedules [69–71]. Charef [72] claimed that using BIM throughout the project life cycle improves project efficiency, resulting in a significant shift in how assets are planned, designed, managed, and deconstructed. In addition, the BIM model allows upfront entry of component properties, allowing for traceability from procurement to installation. Furthermore, Juan and Hsing [73] added that BIM has applications in renovations and building maintenance. A BIM system with a high level of integration and add-ins can support interoperability [74]. The BIM process incorporates risk management techniques and opens communication channels for all stakeholders. By providing a simulated environment, BIM assists architects, engineers, and constructors in visualising future construction and identifying potential design, construction, or operational challenges [75].

The potential of building information modeling (BIM) extends beyond its application in traditional building projects. It can also be implemented in various construction fields such as roads, tunnels, railways, earthwork, mass transit hubs, utility, and energy infrastructures [76]. Additionally, specialised forms of BIM have been developed to address industry needs, including Civil/Construction Information Modeling (CIM), Bridge Information Modeling (BrIM), Road Information Modeling (RIM), and Tunnel Information Modeling (TIM) [77]. In line with these advancements, another significant development is I-BIM (Infrastructure Building Information Modeling) which is a comprehensive platform for effectively managing various aspects of infrastructure development, such as geotechnical underground works [78] and transportation infrastructures [76]. Furthermore, the integration of BIM with a Geographic Information System (GIS) has been studied by Sharafat et al. [79] to enhance the overall efficiency of managing underground utilities. According to Fakhimi et al. [80], BIM has the potential to be a powerful conceptual strategy that can be implemented in the lifecycle of oil, gas, and petrochemical projects.

The development of BIM involves more than just 3D modelling. It covers 4D (Scheduling), 5D (cost estimation), 6D (sustainability), and 7D (facility management) [81,82]. Charef [72] highlighted the BIM models in the context of CE and proposed assigning the eighth model (8D) to the activities associated with sustainable end-of-life management. Kanters [52] stated that model 7D has significant benefits in design for deconstruction as it has comprehensive information on various aspects such as materials specifications, location of building embedded elements, and maintenance schedules.

Several authors developed a BIM-based tool for circularity. For instance, Akinade et al. [83] developed a BIM-based deconstruction assessment score (BIM–DAS) that evaluates the building deconstruction level and provides end-of-life information at the design stage. Akinade et al. [84] developed a BIM-based Whole-life Performance Estimator (BWPE) to assess the performance of structural components during design and interact with Material Passports to manage building performance and restoration when needed. Akinade and Oyedele [85] developed a computational tool that integrates a BIM platform with an Adaptive Neuro-Fuzzy Inference System (ANFIS) to predict and report construction waste in the supply chain.

3.4. Role of BIM in Overcoming CE Barriers

Despite the current design strategies and innovations in buildings' materials and components, there are still barriers to implementing CE [11,12,17–20,27,86–88]. Building developers are progressively becoming aware of CE and regenerative design concepts, although they do not have a unified definition or comprehension [21]. Implementing CE design strategies in buildings remains challenging due to several barriers. The most cited barriers found in the literature are lack of practical guidelines and design-support tools that facilitate CE implementation [15,18,45,88,89], lack of understanding/skills on how to apply the principles of the circular economy [11–13,20–22], lack of incentives [12–14,20,21], difficulty in building data management [14,27–29,90], lack of holistic approach among supply chain [11,13,16,17,23,51], lack of trust/interest to infuse circularity [11,17,19,91], high upfront cost investment [14,18–20,92], and building complexity [11,13,14,56,93,94]. Table 1 lists CE barriers found in the literature.

Several studies have identified barriers that hinder the implementation of CE principles in buildings. Purchase et al. [22] discussed the challenges of transitioning from a linear economy to a circular economy in the construction and demolition (C&D) waste sector. Adams et al. [11] conducted an electronic survey to understand the CE awareness level and to identify CE barriers in the construction sector. Kanters [90] conducted a series of interviews with consultants and architects with experience in circular building design to identify the barriers and drivers of the transformation. Akinade et al. [15] identified 26 critical barriers to design for deconstruction practices through six focus group interviews. Oluleye et al. [10] systematically reviewed the literature and identified 33 barriers to CE adoption in building construction and demolition waste management. Rios et al. [12] conducted a study to identify potential barriers to designing circular buildings in the United States and to comprehend the barriers and differences between the United States and European countries. Other studies identified the barriers to reusing building materials and components [86,95], focusing on structural steel reuse barriers [13].

Table 1. List of CE barriers found in the literature.

No.	Code	Category	Barrier	Reference
1	A1	Awareness	Lack of understanding/skills in applying the principles of the circular economy	[11–13,15,18]
2	A2	Awareness	Fragment supply chain	[11,13,16,17,23,51]
3	A3	Awareness	Lack of global vision	[17,19,21]
4	A4	Awareness	Lack of adequate information in building design/Lack of information about existing structure and material	[13,29,86,96]
5	A5	Awareness	Lack of information about the availability of reclaimed materials	[29,86]
6	T1	Technical	Building complexity	[11,13,14,56,93,94]
7	T2	Technical	Lack of common materials classification	[15,97]
8	T3	Technical	Lack of traceability systems	[88,97]
9	T4	Technical	Difficulty in building data management	[14,27–29,90]
10	T5	Technical	Lack of knowledge on quality and quantities of reclaimed materials	[12,15,88]
11	T6	Technical	Difficulty in identifying reclaimed components/No information exchange system for salvaged materials	[15,28,29]
12	T7	Technical	Lack of standardisation/specifications for reused and recycled materials	[86,94]
13	E1	Economic and market	Estimation challenges	[29]
14	E2	Economic and market	Lack of market mechanisms for recovery	[11,15,16,45]
15	E3	Economic and market	A mismatch between the supply and demand of reused materials	[13,86,89]
16	E4	Economic and market	Lack of global vision of life cycle cost	[12,21,29]
17	I1	Implementation	Lack of understanding among management on issues related to circularity in building	[29]
18	I2	Implementation	Lack of storage facilities	[15,23,29,51]
19	S1	Social	Wrong perception of building circularity	[12,22,28,29,56,98]
20	S2	Social	Lack of trust/interest to infuse circularity	[11,17,19,91]
21	P1	Support/promotion	Lack of incentives	[11–13,20–22]
22	P2	Support/promotion	Lack of insurance for reclaimed materials	[29]

Charef and Emmitt [29] highlighted seven new ways to use BIM to overcome CE barriers. The seven new BIM uses were: a digital model for Sustainable End-of-Life (SEoL), a material passport development that stores information about building materials, a project database that stores information about the entire building process, a data checking process which makes sure that the data meet the desired requirements, a circularity assessment which evaluates the sustainability and life cycle of building materials, materials recovery processes which help facilities the reclaiming and recycling of materials, and materials bank which store information about material types.

In this study, we identified 14 ways to use BIM as an enabler to overcome CE barriers. These are:

1. Digital modelling for end-of-life: BIM can provide comprehensive information that aids the decision-making regarding the reuse, repair, recycle of building materials and components at the end of a building life cycle. Digital modelling for end-of-life in BIM enhances understanding, skills, and global vision in circular economy principles by providing a visual platform and promoting collaboration and data sharing for stakeholders to comprehend the environmental and economic implications in the entire lifecycle of a building. As a result, stakeholders can make informed decisions and adopt effective circular strategies. Furthermore, it integrates comprehensive data on material characteristics, performance, and potential end-of-life scenarios, empowering designers to make informed decisions that prioritise circularity from the early stages. Additionally, by analysing complex building systems, designers can ensure efficient use of material flow and increase trust in circular design strategies. Digital BIM modelling also overcomes data management and estimation challenges by streamlining processes and accurately estimating resource requirements and potential reclamation.
2. Circularity assessment: BIM can provide building end-of-life scenarios, identify opportunities to minimise waste during construction, operation, and deconstruction phases, enhance sustainable material selection, and provide efficiency analysis. Circularity assessment in BIM enhances understanding and skills by providing a systematic framework to evaluate and quantify the circularity of building designs. It helps stakeholders assess the environmental and economic impacts of different design choices, materials, and processes, thereby fostering a deeper understanding of circular economy principles and their application. By Incorporating circularity assessment in BIM, management can better understand the issues and challenges related to circularity in buildings. The assessment process highlights the potential benefits and identifies areas for improvement, allowing management to make informed decisions and develop strategies that prioritise circularity. Moreover, circularity assessment in BIM helps counter the wrong perception of building circularity by showing the environmental and economic advantages of circular approaches and potential cost and savings.
3. Building as material banks: BIM can provide detailed knowledge of the materials used in a building, their location, condition, and potential for reuse or recycling, as well as inventory management. BIM allows for the digital representation and management of building materials by tracking and managing the lifecycle of materials. This enables efficient material reuse and recycling, reducing the need for extracting new resources and minimising waste. Having a database about each material used in the building can be accessed and enhance designers, architects, and contractors' knowledge during the design and construction phases, promoting the reuse of materials rather than sourcing new ones. BIM can be integrated with inventory management systems to keep track of materials. As materials are added or removed, the system updates the inventory, providing real-time information on available resources. This increased visibility and accessibility of reusable materials facilitate the growth of the reused market by providing a reliable and convenient source for construction projects. The existence of a material bank creates incentives for project teams to prioritise material reuse, as it reduces the need for purchasing new materials and lowers project costs.

4. Simulating circular processes: BIM can simulate circular design strategies such as design for deconstruction/disassembly. BIM simulations can enhance comprehension and engagement among professionals and stakeholders of circular strategies by visualising circular economy practices, facilitating learning and knowledge transfer. This enables individuals to gain the necessary skills to apply circular economy principles effectively. BIM can simplify the building complexity to implement circular practises by simulating complex building systems and guiding designers in selecting the best circular design options.
5. Integrated learning: BIM integrates various aspects of building design and construction, which provide a comprehensive learning experience that covers multiple disciplines that allow the professionals to be educated about the circular economy practises, including reducing waste, reusing materials, and designing for deconstruction. BIM can enhance understanding and develop skills related to the application of circular economy principles by providing a digital platform that integrates various aspects of circular construction projects, including circular design, material reuse, resource optimisation, and lifecycle analysis. By integrating circular economy principles into BIM training, professionals can explore different design scenarios, assess the circularity performance, and make informed decisions based on quantitative data.
6. Virtual walkthroughs: BIM can provide the stakeholders with a 3D building visualisation to identify potential design issues or conflicts. Virtual walkthroughs provide detailed visualisation experiences that enhance decision-making by offering comprehensive information and allowing exploration of design options, moving through different building areas, observing the spatial layout, and examining interior and exterior elements. They enable the assessment of structures and materials for circularity. Through virtual walkthroughs, professionals can practically apply circular economy principles, improving their understanding and skills while providing a positive and trusted perception of circular economy practices.
7. Collaboration and communication platform: BIM can facilitate interdisciplinary collaboration among supply chain engineers, architects, contractors, designers, and facility managers. BIM facilitates Integrated communication and coordination among supply chains, promoting collaboration and a unified approach to circularity. By providing a shared digital environment, the platform enhances information exchange and integration during the design phase, ensuring comprehensive and circular design practices allowing the supply chain to make informed decisions about circularity and simplifying data management. The platform supports efficient data storing and sharing, ensuring relevant information is readily available to all stakeholders, promoting transparency and facilitating circular decision-making.
8. Data tracking and traceability: From materials sourcing to transportation to installation and deconstruction, BIM can provide stakeholders with access to the material tracking information. Stakeholders can access detailed information about the materials used in a project. This information can include the specific type of material, its source, supplier details, environmental characteristics, and other relevant attributes. Integrating this data into the BIM model makes it possible to track and trace the entire lifecycle of materials. BIM can facilitate the planning and execution of modern buildings more efficiently. It provides better traceability and improves data management by serving as a central interface for transferring, storing, and retrieving information about a building. As a result of transparent BIM, stakeholder trust can be enhanced by demonstrating the benefits of circularity, including reduced lifecycle costs and resource efficiency.
9. Material passports: BIM can incorporate detailed data sheets about the environmental performance, information about its properties, and circular potential of specific materials. By incorporating material passports into BIM, each material used in a project can be assigned a unique identification code or tag. This allows for easy identification and traceability of materials throughout the construction process. It becomes

possible to track each material's origin, quality, and sustainability aspects, ensuring transparency and accountability in the supply chain. By having information about a material's properties, condition, and potential for future use, stakeholders can identify material recovery and reuse opportunities. Having a material passport can overcome the wrong perception and build trust in reused materials, providing transparent and reliable information about their properties, condition, and history.

10. Clash detection: Before construction, BIM can identify and resolve spatial conflicts (clashes) between building components, systems, and elements. BIM involves analysing the various building elements and systems to identify conflicts in spatial coordination. This process helps to uncover potential clashes early in the design phase, including clashes between circular economy elements such as material flows, waste management systems, and energy efficiency measures. By identifying clashes, the design team can make necessary adjustments to ensure a more streamlined and efficient circular design. Clash detection can navigate the complexity of circularity in building design and construction, leading to a more successful integration of circular economy principles.
11. Standardised material library: BIM facilitates the standardisation of materials, including details about their properties, performance, and environmental impacts. Project participants can select materials based on sustainability, energy efficiency, or compliance with specific regulations. The library can also provide cost information, allowing the participants to make informed choices about materials.
12. LCC and cost estimation analysis: By using BIM, stakeholders can get a comprehensive picture of the building's life cycle cost, which includes design, construction, operation, maintenance, and end-of-life costs. The BIM process provides comprehensive and accurate information about every aspect of a building, from materials to design to structural elements, in terms of the LCC. As a result of more accurate cost estimates, circular economy stargates can overcome the difficulty of cost estimation in implementing these stargates, as they allow for more precise budgets and resource allocations.
13. Estimation software integration: Integrating the cost estimation software into BIM streamlines the estimation process and ensures consistency between design and cost information. Through precise and detailed data, BIM facilitates more accurate cost estimates, including material, labour, equipment, and risks. BIM reduces errors, and consistency is enhanced by automatically updating cost estimates when changes occur in design or materials. Moreover, automation leads to more efficient quantity take-off for cost estimation. Allowing stakeholders to communicate effectively through visual representations and reduce cost estimate disagreements. Further, BIM reduces uncertainties by predicting cost overruns. By providing a comprehensive view of project costs throughout a project's design, construction, and operation phases, BIM helps manage project costs throughout its life cycle. It also informs future projects. BIM also enables early identification of potential risk factors, contributing to better risk management and cost estimation.
14. Integrated information management: By integrating information about design, construction, and facility management, the BIM process serves as a common resource to all stakeholders. BIM provides a comprehensive understanding of the building lifecycle by integrating design, construction, and facility management information. BIM enables accurate space planning and optimisation, allowing stakeholders to visualise and analyse storage requirements within a building or facility. It allows engineers and project managers to accurately visualise and plan the storage areas, considering various factors such as available space, accessibility, and storage capacity, enabling informed decisions about design and optimisation.

Table 2 links CE barriers and BIM used as an enabler.

Table 2. BIM uses as an enabler to overcome CE barriers.

Barrier Code	BIM Uses as Enabler to CE Barriers													
	Digital Modelling for End-of-Life	Circularity Assessment	Building as Material Banks	Simulating Circular Processes	Integrated Learning	Virtual Walkthroughs	Collaboration and Communication Platform	Data Tracking and Traceability	Material Passports	Clash Detection	Standardised Material Library	LCC and Cost Estimation Analysis	Estimation Software Integration	Integrated Information Management
A1	✓	✓	✓	✓	✓	✓			✓					
A2							✓	✓						✓
A3	✓		✓		✓				✓					
A4	✓					✓	✓	✓						
A5			✓				✓		✓					
T1	✓			✓			✓	✓	✓	✓				
T2			✓				✓		✓		✓			
T3	✓						✓	✓	✓					
T4	✓		✓				✓	✓						
T5	✓		✓						✓					
T6	✓		✓						✓					
T7			✓				✓		✓					
E1	✓								✓			✓	✓	
E2			✓						✓					
E3			✓						✓					
E4	✓								✓			✓		
I1	✓	✓												
I2	✓													✓
S1	✓	✓	✓		✓	✓			✓					
S2	✓	✓	✓			✓	✓	✓	✓					
P1			✓						✓					
P2			✓								✓			

3.5. Role of BIM in Enhancing the Life Cycle Cost of Circular Construction of Buildings

Life cycle cost is employed in building projects to provide a comprehensive view of costs, evaluate the benefits and effects of various design options to identify the optimal solution for the project [99], and assist in decision-making [100]. The LCC process analyses all costs associated with a construction project, operation, maintenance, service, and disposal [99]. Warren and Weitz [101] defined the LCC as "all internal and external costs associated with a product, process, project, or activity throughout its entire life cycle from raw materials acquisition to recycling/final disposal of waste materials". Lee et al. [102] added that a building's life cycle cost is the sum of all fundamental processes that take place over the life cycle of a building. LCC includes planning, obtaining paperwork, implementing environmental management measures before construction starts, dismantling, maintenance, and disposal [102].

Lee's [103] research focused on developing an LCC/LCA model that can be used effectively in a BIM environment. Providing this information database with LCC information relating to building materials has been a significant undertaking. The model applicability was demonstrated by examining two indoor flooring materials commonly used in Korean residential structures. Santos et al. [104] have developed a prototype BIM-based Environmental and Economic Life Cycle Assessment (BIMEELCA) that integrates BIM with LCC and LCA in the construction industry. Using this BIM-based framework, economic and environmental assessments were evaluated in construction projects. Based on the findings, the model may improve cost estimation, promote sustainability, reduce human error, and reduce the time devoted to assessing sustainability. BIM has been integrated with LCC and LCA to address their limitations, significantly impacting the development of automated simulation models for sustainability in the construction industry.

According to Yuan et al. [105], integrating BIM and Value Engineering can help optimise green buildings by reducing energy consumption and maximising life cycle costs. The researchers developed a framework for energy-saving architecture in response to the growing energy crisis and global warming. According to the study, this integration could enhance energy-saving strategies for architectural designs and promote sustainability. A study by Zoghi and Kim [36] investigated the benefits of BIM in reducing construction waste and improving LCC analyses. Using a system dynamic (SD) model results in a 70% reduction in construction costs and a reduction in landfill costs. The researchers validated their findings by examining a 12-story commercial building in Canada as a case study. Azhar [68] asserted that using BIM enhances collaboration among project teams, resulting in increased profitability, reduced expenses, and improved time management.

LCC can switch to CE by integrating BIM into LCC for economic and environmental sustainability. Using BIM has several benefits as BIM saves time, estimates costs, minimises changes, analyses sustainability, eliminates omissions, manages quality and logistics, establishes life cycles, manages LCC, ensures energy efficiency, facility management, daylight analysis, thermal design, transparency costs, quantity surveys, quantity takeoff, among other benefits [81,106–108].

Buyle et al. [109] reported that circular design alternatives are considered for internal wall assemblies in Belgium. In this study, life cycle assessment and life cycle costing were employed to determine the impacts of the assembly on the environment and the economy. In addition, wall assemblies that can be demounted and reassembled have a life cycle cost of 10% and 17% lower than conventional alternatives. However, the study emphasises the importance of conducting a comprehensive sustainability assessment before making conclusions.

On the other hand, a study by Kaddoura et al. [110] examined five real-life cases of extending the lifetime of passive products by using Product Service Systems (PSS), such as furniture, and signs, to determine whether such systems can be implemented. As a result of the study, most cases experienced a reduction in environmental impacts, measured by global warming potential, of 45–72%; however, manufacturers experienced a decline in life cycle costs by 8–37%. As a result of these reductions, a circular economy can be achieved through PSS and increase the willingness of the companies to accept changes.

Consequently, BIM is essential in promoting sustainable practices by enhancing the LCC of circular construction. As a result of BIM, various building aspects are integrated, including design, construction, and maintenance, reducing waste, and extending the longevity of materials throughout the construction process. Circular construction in the building industry can be improved by streamlining decision-making processes and facilitating collaborative efforts among stakeholders through BIM. Figure 3 illustrates the BIM integration in circular construction and LCC.

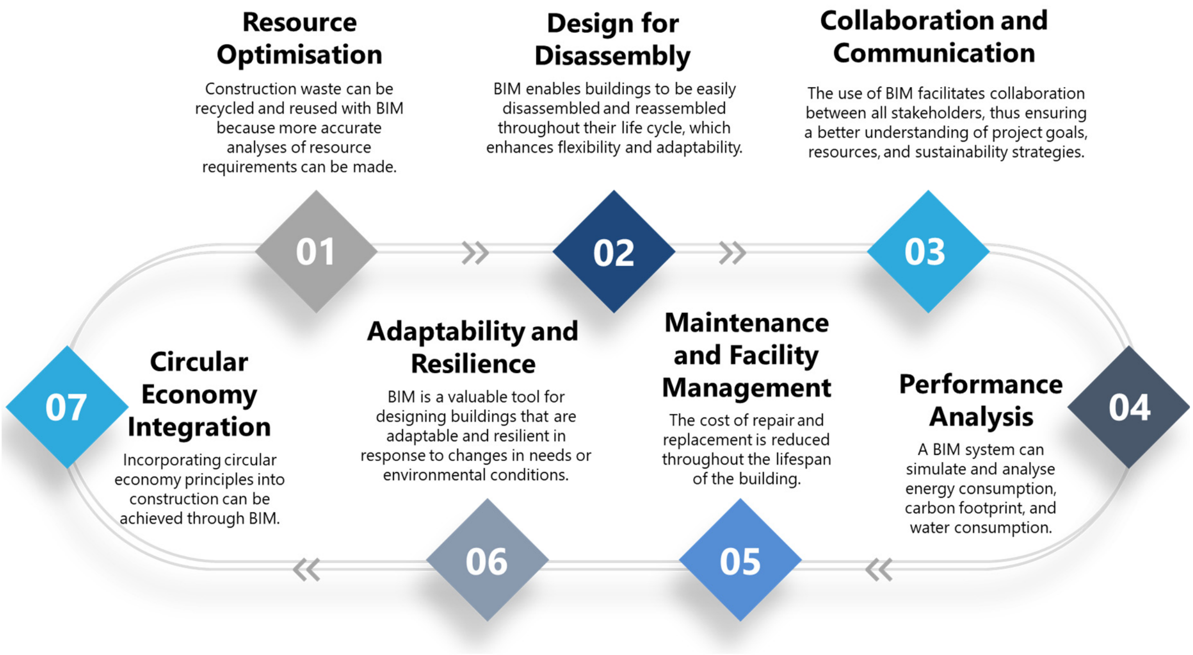

Figure 3. BIM in circular construction contributes to an enhanced understanding of LCC.

4. Conclusions

A literature review of 88 articles was conducted to explore the current practices in circular building design and LCC analyses by using BIM. The study identified 22 barriers hindering the successful implementation of circular economy principles in the building industry. These barriers were categorised into six groups: awareness, technical, economic and market, implantation, social, and support/promotion.

The study discussed the role of BIM as an enabler to overcome CE barriers. We identified 14 BIM uses to overcome these barriers, which were: digital model of end-of-life, circularity assessment, building as material banks, simulating circular processes, integrated learning, virtual walkthroughs, collaboration and communication platform, data tracking and traceability, material passports, clash detection, standardised material library, LCC and cost estimation analysis, estimation software integration, integrated information management.

The use of BIM in managing a building's end-of-life remains relatively uncommon. Therefore, this study highlighted the significant potential of BIM for enhancing LCC in the circular construction of buildings. The study concluded that BIM could be a valuable tool for improving LCC in circular buildings by providing a comprehensive prospect of the building's life cycle and enabling efficient decision-making.

In addition, the study discussed the role of the circular economy approach in terms of environmental and economic aspects. Circular buildings have the potential to reduce the LCC. Integrating BIM into the design process makes it possible to predict and simulate LCC more accurately while maintaining building performance requirements. Furthermore, BIM provides an accurate and comprehensive information exchange platform that facilitates efficient coordination among all stakeholders throughout the project lifecycle.

Using BIM in circular buildings can reduce construction and maintenance costs and provide valuable information for future renovations and deconstructions. Some challenges remain despite the potential benefits of BIM and LCC analyses with CE for building construction and maintenance. As a result of these unique characteristics, BIM and LCC in Circular Economy analysis are more challenging to implement. This is due to their long-life cycle, complex part composition, and split incentives among multiple stakeholders. Moreover, the industry is also still experiencing concerns regarding data quality and lack of standardisation.

It is important to note that, despite these challenges, the construction industry can overcome these challenges by adopting and developing BIM and LCC in Circular Economy standards, as well as utilising technological innovations to facilitate the adoption and development of sustainable and efficient building practices that will positively impact the environment, society, and economy. As a result, BIM coupled with LCC in Circular Economy analysis offers a promising solution to address the sustainability and efficiency challenges the construction industry faces.

The study limitation is the lack of practical case studies demonstrating the successful implementation of BIM in circular construction projects. To overcome this limitation, future research should investigate the feasibility of using BIM applications in real-life scenarios and conduct case studies specifically on circular building construction. Moreover, it is crucial to establish a comprehensive priority ranking of the barriers hindering the implementation of circular buildings and the role of BIM as an enabler. This ranking should be developed in collaboration with built environment professionals to ensure a streamlined approach towards implementing circular building practices.

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