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Circular economy in construction: The digital transformation perspective

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ABSTRACT

This systematic review critically examines the intersection of digital transformation and circular economy (CE) principles within the built environment. While digitalisation has been shown to enhance efficiency, safety, and sustainability in construction, its role in fostering circularity is less established. This study analyzes literature from 2010 to 2022, focusing on how digital technologies such as open-BIM, digital twins, material passports, blockchain, RFID, and gamification can integrate into and enhance the circular building lifecycle. The findings reveal that while digital tools are pivotal in design and construction phases, their application to existing structures is less straightforward, with challenges including the absence of digital twins for demolished structures, the high costs of retrofit digitalisation, and the predominant focus on environmental benefits over practical implementation. The review also highlights the need for a unified digital transformation strategy and greater cross-industry collaboration. Future research directions are proposed, including the development of localized material banks, the application of RFID in circularity, the scope of Design for Disassembly (DfD) tools, digital inventory of existing buildings, the circularity of Life Cycle Assessment (LCA) databases, and policy implications for promoting circular construction practices.

1. Introduction

The environmental damage due to the increased urbanisation, extensive use of virgin materials in construction and subsequent waste generation at the buildings' End of Life (EoL) stage have spiked interest in developing alternatives, more sustainable, circular business models. The circular construction industry would see the incorporation of Circular Economy (CE) principles throughout the built environment; however, it is at its early stages. Pomponi and Moncaster (2017) argue that the construction division of the built environment is leading the pack when it comes to circularity. Though, as an idea, CE does not promote the implementation of its principles in one stage of an industry, but rather a blanket approach that incorporates the principles at every stage of the project, cradle to cradle approach (Mulhall and Braungart, 2010). Jones and Comfort (2018, 7) state that "ideally the circular economy should involve the whole of the construction supply chain", implying that through a comprehensive approach, the goals of CE could be achieved. The sweeping incorporation of CE principles means that it must be observed at the building components manufacturing stage (Giama and Papadopoulus, 2020), the transportation of the materials (Nasir et al., 2017) design stage (Eberhardt et al., 2020), throughout the life of the building (Windapo and Moghayedi, 2020) and at its very end (Ruiz et al., 2020).

Any construction development of an urban environment starts with the idea informing the design process, guiding the subsequent and cooperative branches toward a final product. In her thesis, Tingley (2013, 165) suggests buildings designed for deconstruction as a "strategy to increase future supply chains". The design directs the construction segment of the industry as the purpose of the building is introduced, ensuring that the material used does complement the intended circularity (Tingley, 2013). The maintenance stage of the building life also must function in a way that executes the intended circularity, ensuring that the life of a building and its functionality do not deviate from the circular principles (Akhimien et al., 2021). Building parts are recovered and carefully reused at the deconstruction stage based on their functionality or repurposed and adapted to new use, where a cycle begins

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again (Ruiz et al., 2020). Hence, as CE and built environment are in the novice stage of their relationship, it is acceptable to discuss branches exceeding others in the CE principles applicability; however, the tendency and desire to revolutionise the whole industry must be present, as Remøy et al. (2019) argue nothing less than systematic application.

The design of the building is the most critical stage at which the ideas converge and where the circularity of the building is considered. Joensuu et al. (2020) highlight the designing-out-waste importance of the project planning stage. The planned use of recycled materials or even the reuse of the old building components would ensure that 'waste' is eliminated. Also, carefully planning the future use of the materials forming an integral part of the new building ensures the elimination of waste at the end-of-life stage. However, not all building components could be removed in pristine condition. The design-for-adaptation or design-for-repair can also become an integral part of the design, "enabling expanding life cycle of component or product" (Joensuu et al., 2020, 9). Anastasiades et al. (2020) argue that when design-for-adaptability and design-for-disassembly are combined, the preservation of the building is also possible, as the parts could be easily removed, modified, and repaired, without compromising the structure.

Furthermore, Akbarieh et al. (2020) argue that design for deconstruction is essential in disposing of building sustainably. Planning for the inevitable buildings deconstruction stage is not a novelty in the construction industry; however, it is far from achieving the targeted minimisation of construction and demolition waste (CDW) (Akinadeh et al., 2020). Akinade et al. (2020) underline that if the plan for deconstruction is not incorporated at the design stage, efficient material recovery will not be possible at the end-of-life phase. However, this must be underlined that the design stage of the building, incorporating deconstruction and reuse of the building components, must ensure that the components used are compatible for eventual reuse.

Achieving the complete incorporation of the CE principles at every stage of a building's life, from 'cradle to cradle', is not an easy process. The desire and willingness to create a circular construction must be combined with means and methods to achieve it. A well-meaning designer must-have tools and materials available to plan a circular project. Hence, this cannot be achieved if other collaborating industries do not embrace CE. de Sousa Jabbour et al. (2018) and Ul Haq and Francheschini (2019) argue that digital manufacturing is the key to unlocking the circularity of the supply chain, and Bekrar (2021) states that the same is valid for the transportation sector.

The digital transformation of the construction industry has undeniably provided stakeholders with robust tools at every project phase, enhancing collaboration, expediting design and construction processes, optimizing building maintenance, and ensuring responsible end-of-life (EoL) disposal. Despite these advancements, there remains a discernible disconnect between the operational improvements brought about by digital technologies and the principles of circular economy (CE) that advocate for resource efficiency and regenerative design. This disjunction underscores a critical knowledge gap: the integration of CE principles is not yet a widespread or intrinsic part of the industry's digital transformation.

This study, therefore, embarks on a scholarly inquiry to bridge this gap, investigating the current state of literature on how the digital transformation within the built environment can embrace and operationalize circularity. By presenting a conceptual review and establishing a frame of reference for both CE and digital transformation, this research aims to illuminate the synergies and fissures between these two pivotal domains. The systematic review method, meticulously applied to canvass literature from Scopus, Web of Science, and Google Scholar spanning from the first of 2010 to the end of 2022, serves as the foundation for this exploration.

The resultant analysis delves into the emergent themes and identifies the lacunae in effectively weaving digital transformation technologies and processes into the fabric of a circular building lifecycle. The scientific impetus for this review is twofold: firstly, to consolidate the fragmented insights on digital and circular practices within the construction sector, and secondly, to chart a course for future research that can catalyze the transition to a more sustainable and digitally integrated industry. In doing so, this study not only contributes to academic discourse but also propels practical advancements towards a circular and digitally adept construction paradigm.

2. Conceptual review and frame of reference

2.1. Circular economy

Manufacturing goods designed for single use has been an integral part of the linear economy for a long time. However, population growth and increased consumerism created a plausible concern that some of these valuable raw materials are becoming scarcer, costly, and potentially depleted (Adams et al., 2017). Therefore, finding an alternative to a linear economy is necessary and detrimental to the continuity of any industry. Boulding, in his seminal study, spoke of the closed economy of the future in which "the earth has become a single spaceship, without unlimited reservoirs of anything … and in which, therefore, man must find his place in the cyclical ecological system" (Boulding, 1992, p. 31). He states that the difference between the closed economy of the future and the current economy is how it views consumerism and production levels. Unsaturated consumption, unchecked production and use of raw materials are the measures of success in the current economy, while the economy of the future measures its success in "nature, extent, quality, and complexity of total capital stock" (Boulding, 1992, 31). The fact that Earth's raw materials are depleting is not a piece of new information; however, the idea of finding a substitute for virgin materials took off with the reports on CE published by Ellen MacArthur Foundation.

The 2013 publication focused on comparatively analysing both linear and CE, highlighting the adverse impact linear economy had and still does on the environment while simultaneously engraving the idea of an inevitable switch to circularity (MacArthur, 2013). The report defines CE as "an industrial system that is restorative or regenerative by intention and design" (2013, 7), firmly focusing on the profitability of the opportunity (2013, 9). The definition speaks of a deliberate movement towards circularity in business models.

The CE practice resides on three basic principles. First, the 'designing out waste' is at the core of the CE. The assertion that "waste does not exist" forces the industry to move in the direction of product design for the purpose of disassembly, adaptation, and reuse (MacArthur, 2013, 7). To accommodate the elimination of waste, CE is trying to incorporate the idea of a user rather than the consumer, thus minimising the products' perishability, limiting them only to biodegradable, non-toxic elements and those whose durability warrants reuse. Hence, the durable products in the hands of a user will find their way to the economy as a material for new products, repurposed objects or retain their functionality as reusable merchandise, which is the goal of CE. The final principle addresses the energy used to power the CE cycle, which must be renewable and sustainable. The direct reusability of the product ensures a reduction in energy consumption, leading to environmental benefits and overall profitability.

Adams et al. (2017) argued that the concept of CE in the construction industry is in its infancy, mainly limited to minimising waste and recycling. This study will assess the digital transformation paired with CE, which could, in a small measure, assist its maturity in the built environment.

2.2. Digital transformation

The digitalisation of any industry leads towards "multiple value creation mechanisms" and better use of resources (Nasiri et al., 2017, 5) as well as the enhanced ability to link numerous stakeholders creating a fertile ground for innovation (Simonsson and Magnusson, 2018). The digital transformation of the built environment involves "the automation of all stages and procedures throughout the entire lifecycle of an object" (Esetova et al., 2019, 2). Ávila-Gutiérrez et al. (2020) argue that the benefits of digital transformation in the construction industry relate to creating new opportunities, increasing efficiency, reducing complexities and general sustainability. The computation of the construction industry has also opened the door to the innovative use of building materials (Janakieska et al., 2019). Furthermore, Antikainen et al. (2018) argue that digitalisation enables the drop in energy intake, streamlines the logistical processes, ensures waste reduction, and renders greater access to product lifecycle data related to its use and potential for reuse. Building information modelling (BIM) is the globally recognisable digital platform used in the construction industry. It is used to create virtual replicas of the new and existing physical facilities. Virtual models of the actual structures contain data regarding the size and form of the structure, and material inventories are used throughout the facility's lifecycle. When incorporated with other digital technologies, such as Blockchain or EoL tools, BIM acts as a connector between all relevant stakeholders, thus streamlining the processes and increasing efficiency (Esetova et al., 2019). These trimmed-down processes are not necessarily circular but are becoming sustainable, and managing the business sustainably is one of the steps in CE. This study will examine the state of digital transformation in CE principles and its integration within the construction industry that goes beyond the current sustainable business models. This refers to the innovative approaches that transcend traditional practices, incorporating principles of the circular economy, digital integration, and regenerative design.

3. Materials and methods

3.1. Systematic literature review

The systematic literature review was used as the principal source of data generated from literature related to digital transformation in a built environment incorporating the CE principles. The superiority of the systematic literature review lies in synthesising all literature discussing the selected topic (Tight, 2019). Suri and Clarke (2009), in their review of data synthesising methods in research, highlighted three general guiding principles: "informed subjectivity and reflexivity, purposefully informed selective inclusivity, and audience-appropriate transparency" (408–413), underlining the nature of the systematic review and how the researcher's bias could impact it. Hence, there is a need to incorporate guiding principles to ensure the transparency and replicability of the review. Therefore, the search for the literature was conducted focused, purposefully selecting only literature that discussed the topic this project intends to examine.

3.1.1. Inclusion criteria

- Peer-reviewed articles published between January 2010 and December 2022.
- Articles that explicitly discuss digital transformation in the context of CE within the built environment.
- Studies that provide insights into the application of digital technologies in advancing CE principles in construction.

3.1.2. Exclusion criteria

- Non-peer-reviewed literature, grey literature, and unpublished works.
- Articles not written in English.
- Studies that do not directly address the intersection of digital transformation and CE within the built environment.
- Publications that focus on industries outside of the construction sector, even if they mention relevant terms in their bibliography.

The search was conducted in the *Scopus, Web of Science, and Google Scholar* digital databases available through the University of Canberra Library.

3.1.3. Rationale for database selection

Scopus is a well-known database with the wide coverage of scientific literature including engineering, environmental science, and urban studies relevant to the aim of this study. Its database consists of peer reviewed articles and conference proceedings therefore ensures that the literature used are credible and quality. The advanced search facilities available in Scopus assist with formulating sophisticated literature retrieval search strategies. The tool offers thorough citation analysis that is beneficial in locating seminal studies and assessing their significance toward the subject area (Harzing and Alakangas, 2016).

Google Scholar indexes wider ranges of scholarly works relating to research such as theses, books, abstracts, and articles from academic publishers, professional associations, online repositories, and universities. It is free and has a number of full-text links. This is especially important if an article is missing from the subscription databases. Capacity of the platform in encompassing interdisciplinary works in construction, digital transformation, circular economy and others makes it strong (Harzing and Alakangas, 2016).

Web of Science covers a wide array of high-impact journals, a requisite since there will always be an intersection of technology, sustainability, and construction. It gives historical depth that is vital for comprehending the progression of digital transformation as well as circular economy concept in the construction industry. Strict inclusion criteria of the database guarantee that only credible literature is taken into account, thus making the review more reliable (Harzing and Alakangas, 2016).

Hence, a thorough systematic literature review entails an interdisciplinary pool with high quality and assurance that combines Scopus, Google Scholar and Web of Science. This is why this study uses these databases as to ensure that it captures a comprehensive sphere of publications such as high-impact journals and all accessible online sources, thus providing a holistic overview of the research landscape pertaining to digital transformation and circular economy in the construction industry.

Utilizing all of the analyzed databases, the literature search was systematically recorded in an Excel spreadsheet reflecting the successful searches and those that showed no promising results. The search was limited to the publications from the first of 2010 to the end of 2022 to highlight the digital transformation development in the built environment relating to CE. Furthermore, the position of the term was expanded to all sections of the publications, including the title of the study, abstract, keywords, the body of the text and bibliography. The combining search terms technique was used to ensure the collected literature reflects all necessary aspects this project examines. First combining terms used were "*digital transformation*" AND "*circular economy*" AND "*built environment*", which are at the core of this study. In subsequent searches, the term "*built environment*" was replaced with "*construction industry*", "*building design*", and "*building industry*". A similar method of terminology substitution was done in respect to "circular economy", replacing it with "*resource efficiency*", *circularity*, "*circular business model*" and "*circular model*", and to "*digital transformation*" with use of *digitalisation*, both Australian English and American English spelling. The literature search called for an innovative outlook at search terms, trying to decipher the terms and their combination generally used in the built environment literature, potentially replacing two or all three terms deemed essential for this project. The developed terminology combinations (Table 1) were resulted in 120 publications which were mostly circulated in *Science Direct*, *IEEE Explore*, *IOP Science*, *Springer Link*, and *MDPI* (Table 2).

The further examination of the results exposed that some of the publications were unrelated to the project. The disconnectedness was due to the broad exploration of the texts, particularly the exploration of bibliography, where search engines highlighted the presence of the

Table 1
Terms used to identify and collect relevant literature.

"Built Environment"	**(AND)** "Circular Economy"	**(AND)** "Digital Transformation"
"Construction Industry", Construction, "Building Industry", "Building Design",	"Circular Business Model", Circularity, "Circular Industry", "Circular Model" **LESS SUCCESSFUL** "Climate Change", "Resource Reduction" Depletion, Deficiency	"Digital Adaptation", Digitalisation **SPECIFIC TERMS** BIM

relevant term, i.e., "*construction industry*", while the journal discussed industry other than building construction. Publications that had no relation to the built environment or "*construction industry*" were considered irrelevant and removed from the results. This resulted in a decrease in literature, resulting in 86 publications identified as related. Upon further examination of the text, some publications were identified as highly pertinent on account of their active or even lateral exploration of the use of CE principles in the built environment through applying the digital transformation, 36 publications to be exact. The 50 publications with the necessary components were classified as moderately relevant. They discussed the significance of either the need for the built environment transformation to incorporate CE principles or the need to digitally transform the industry (Fig. 1).

3.2. Thematic and gap analysis

The systematic literature review examines the literature related to the researched topic, which identifies the breadth of the publications addressing the issue and goes deeper in detecting the dominant themes. Thus, identifying themes is an essential part of the research, as it exhibits the knowledge patterns detected by the researcher. Ignatow and Mihalcea (2017, 147) argue that "thematic analysis starts when the researcher notices a pattern of meaning in a collection of texts – either during the process of acquiring the texts or soon after", and subsequently review, define, and name the identified themes (Agyekum et al., 2019). The data collected from the literature in this project was coded into themes, which eased pattern identification. Out of the analysis, four themes emerged related to the main stages a building undergoes in its lifetime, design, construction, maintenance, and EoL stages. Each stage deals with diverse complexities in how to best incorporate the CE principles using digital technology. Some stages exhibited the diversity and innovation in digital technology adaptation (I.e., open-access databases), while other themes struggled in their effort to digitalise their processes (i.e., older structure digital inventory).

Furthermore, the systematic literature review aims to identify the extent of knowledge on a particular topic, mainly if the researchers aim not only to inform the audience but also to identify the shortcomings of the said knowledge. Gap spotting is essential in this instance, as gaps indicate the need for further research. Because of the digital transformation and CE movement being quite a novice for the built environment and the recent boom in the use of digital tools in the construction industry, it is understandable that the literature addressing the problem is in development and lacks uniformity. Therefore, neglect spotting, or at least one of its forms, identifying the under-researched area, is an essential tool in detecting the section of knowledge that ought to be expanded further (Alvesson and Sandberg, 2013). This review will, therefore, show how literature expansively addresses the combination of either of the two terms ("*built environment*", "*circular economy*", and "*digital transformation*") but struggles to put all three comprehensively, or the presence and applicability of three at any and every stage of building's life (Fig. 1). However, we must acknowledge that although the CE immersion in any industry is relatively new, the amount of literature published since the Ellen MacArthur Foundation's first report in 2013 is quite extensive.

Table 2
Publications outlet.

Primary Outlet	Records Number	Publisher	Journal	Conference proceeding
Annals of Operations Research	1	Springer	✓	
Architectural Engineeriong and Design Management	1	Taylor & Francis	✓	
Automation in Construction	2	Elsevier	✓	
Benchmarking	2	Emerald	✓	
Buildings	3	MDPI	✓	
Built Environment Project and Asset Management	1	Emerald	✓	
Clean Technologies and Environmental Policy	1	Springer	✓	
Computers in Industry	1	Elsevier	✓	
EKONOMIAZ	1	IDEAS	✓	
Energies	2	MDPI	✓	
Engeneering Project Organization Journal	1	Eposs	✓	
Espacios	1	Revisita Espacios	✓	
Journal of Cleaner Production	10	Elsevier	✓	
Journal of Construction Engineering and Management	1	ASCE	✓	
Journal of Material Cycles and Waste Management	1	Springer	✓	
Journal of Financial Management of Property and Construction	1	Emerald	✓	
Journal of Information Technology Case and Application Research	1	Routledge	✓	
Journal of Building Engineering	1	Elsevier	✓	
International Journal of Automation Technology	1	J-Stage	✓	
International Journal of Management Cases	1	Glos	✓	
International Journal of Production Economics	1	Elsevier	✓	
International Journal of Production Research	1	Taylor & Francis	✓	
International Journal of Sustainable Built Environment	1	Elsevier	✓	
Procedia CIRP	1	Elsevier	✓	
Renewable and Sustainable Energy Reviews	1	Elsevier	✓	
Resources, Conservation and Recycling	3	Elsevier	✓	
Sustainability	14	MDPI	✓	
Urban Planning	2	Cogitatio	✓	
Applied System Innovation	1	MDPI		
Information Technology in Construction	1	ITCon		
Resources, Conservation & Recycling Advances	1	Elsevier		
Technological Forecasting & Social Change	1	Elsevier		
Robotics & Computer-integrated Manufacturing	1	Elsevier		
Urban Sustainability	1	Nature		
Smart and Sustainable Built Environment	1	Emerald		

(*continued on next page*)

Table 2 (*continued*)

Primary Outlet	Records Number	Publisher	Journal	Conference proceeding
Applied Sciences	1	MDPI		
Busniess Strategy and the Environment	1	Willey		
AIP Conference Proceedings	1	AIP		✓
EG-ICE 2020 Proceedings: Workshop on Inteligent Computing in Engineering	1	ICE Publishing		✓
E3S Web of Conferences	1	EDP Science		✓
Institution of Civil Engineers – Waste and Recourse Management	1	ICE Publishing		✓
International HISER Conference on Advances in Recycling and Management of Construction and Demolition	1	BAMB2020		✓
IOP Conference Series: Earth and Environmental Science	3	IOP Publishing		✓
ISARC Proceedings of the International Symposium on Automation and Robotics in Construction	1	ISARC		✓
Engineering Project Organization Conference (EPOC)	1	EPOC		
2nd World Conference on Waste Management	1	TIIKM Publishing		

3.3. Descriptive analysis

As noted earlier, the literature search resulted in 120 publications, from which 86 publications were selected for analysis after a careful refinement process. The breakdown of the chosen literature is as follows: 10 conference papers, four books/thesis and 71 peer-reviewed journal articles. The researchers limited the publication search to 2010 onwards, and the search did not result in relevant records published before 2016 (Fig. 2). The primary outlets for the major studies and most of them relate to the environmental aspects of industrial operations – Sustainability/MDPI (Switzerland) and Journal of Cleaner Production, Elsevier. The major publications' environmental focus indicates the direction of the current knowledge, which sporadically discusses the digital transformation from the CE perspective. A similar statement applies to the conference papers, as most are published in conferences centred around environmental themes, such as IOP Conference Series: Earth and Environmental Science (Table 2).

Moreover, Fig. 2 displays the distribution of papers during the study period in further details. Since 2016, the number of publications addressing CE in the construction sector has significantly increased and equally peaked in 2020 and 2021.

4. Content analysis: a review of the existing practices of circular economy principles through digital transformation in built environment

The goal of CE in the built environment, beyond waste reduction, is to eliminate the usage of virgin materials and replace those with already used ones, which are almost always a part of current structures. The literature overwhelmingly discusses the BIM application as a base for any attempt to digitalise built environment processes, ranging from green BIM (Olanrewaju et al., 2020) to open BIM databases shared with various stakeholders (Xing et al., 2020). The materials used in existing buildings are recorded in the BIM-created database for that building or could be subsequently created if the building predates the digital age. Akinade et al. (2017) argue that adapting BIM for Design for Deconstruction (DfD), not only accommodates the identification of reusable materials but also improves the collaboration between stakeholders, the conception of deconstruction processes, effective deconstruction planning, "performance analysis and simulation of EoL alternatives", better buildings LCM and "interoperability with existing BIM software". However, Akbarieh et al. (2020) point out that "BIM-based DfD is a mixture of immature or underdeveloped topics with few practical examples", primarily due to the disconnection between the BIM-based DfD and EoL tools. The issue with the breadth of technologies and their interconnectivity is a matter of general technological evolution; however, what is its status with respect to the CE and individual stages in a building's life is examined in this section.

4.1. Digitalised design and circular economy

The design stage is the most crucial step in a building's lifecycle, at which point, stakeholders involved will consciously decide whether to create a circular building or not. Anastasiades et al. (2020) argue that designers are often unaware of the CE importance. Akbarieh et al. (2020) note that designing a building with eventual reuse in the plan is not a new concept in the built environment; however, there is hardly a building designed for deconstruction (Kanters, 2018). The low number of circular buildings could be potentially due to the lack of a globally recognised standard (Cottafava and Ritzen, 2021). Nevertheless, it is understood that every circular building design creates a future-proofed building, generating the potential for adaptability and eventual disassembly or deconstruction (Iyer-Raniga, 2019). The DfD is an additional design step that the design team incorporates into project planning. It involves considering materials used for the construction, such as avoiding toxic constituents and increased use of prefabricated components or modern construction methods, e.g., the use of bolts rather than welding. Kanters (2018) argues that the benefits of DfD eventually lead to "the preservation of embodied energy, the reduction of carbon emissions, and reduction of pollution" (2018, p. 2); however, he also underlines complex DfD processes, whose digitalisation would ease the execution.

Developing a building digital twin by incorporating the CE principles in the design stage creates a materials database and allows for better performance analysis executed through the EoL simulation. Ávila-Gutiérrez et al. (2020) while conceptualising a circular business model founded on eco-holonic architecture, established that in order for the system to work, digital models and simulations must be incorporated into the digital twin. A digital twin represents a virtual copy of an actual building constructed through BIM, containing both the geometric proposition of the building and the materials database used in construction (El Jazzar et al., 2020). The digitalisation of the building design, particularly having a digital twin, also accommodates for records keeping of all changes in materials used and the forms of modifications done. Building designers also employ artificial intelligence (AI) to perform generative and parametric design tasks, allowing them to focus on more complex design issues. The AI's ability to perform multiple simultaneous tasks and generate alternatives for the design (Ernstsen et al., 2021) could also generate circular design options if these were introduced to the system.

Increased incorporation of the DfD using digital tools in the design stage could contribute to the more thoughtful selection of reusable materials utilised for future construction. The BIM-based Whole-life Performance Estimator (BWPE), developed by Akanbi et al. (2018), conducted the three primary building materials appraisal and potential of their reincorporation in the new building. Their findings indicated that steel-based constructions are highly reusable (93%), concrete-based constructions are primarily recyclable, and timber-based ones are split between the two (65% reusable and 35% recyclable). However, the

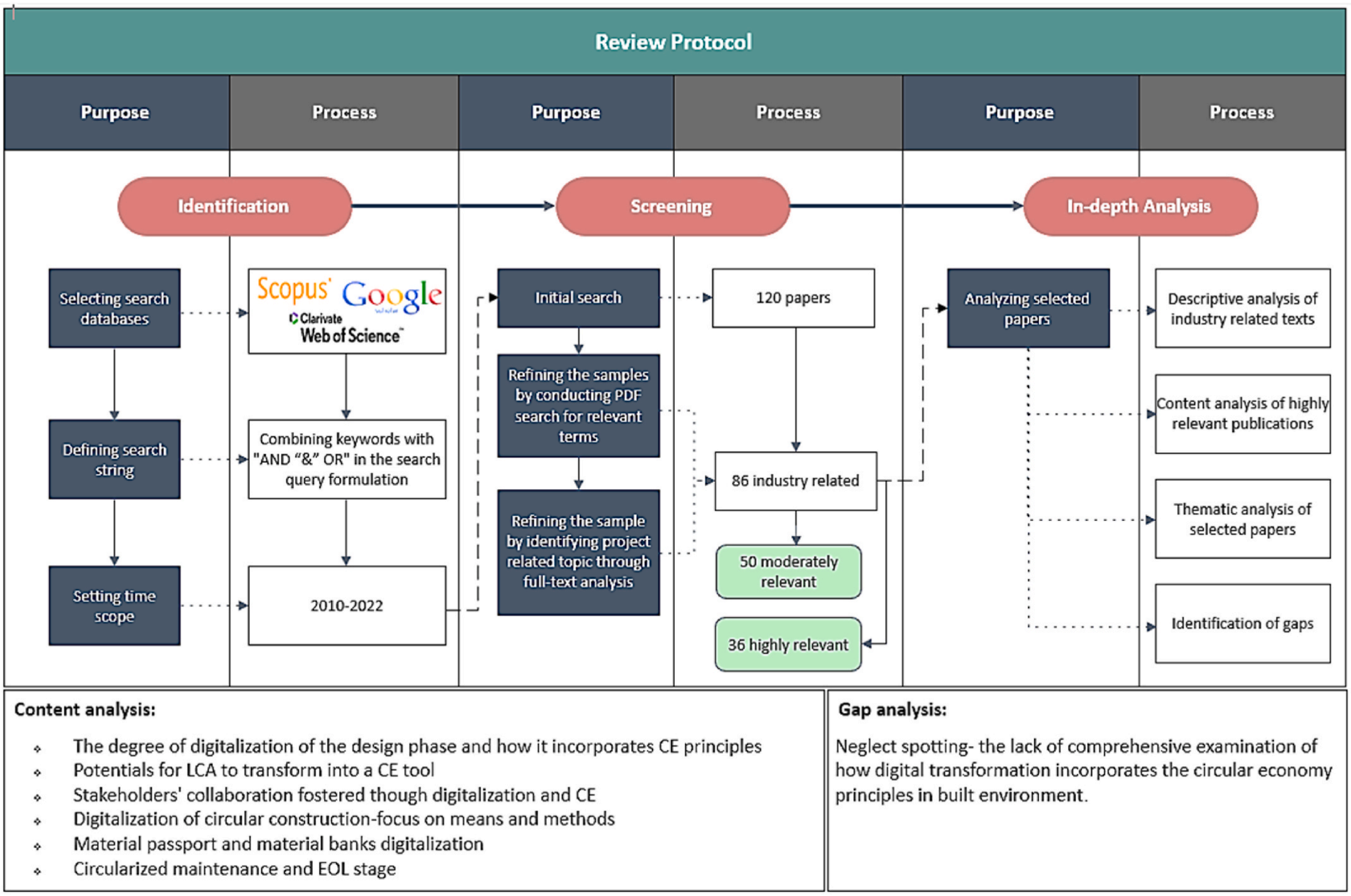

Fig. 1. Materials and methods.

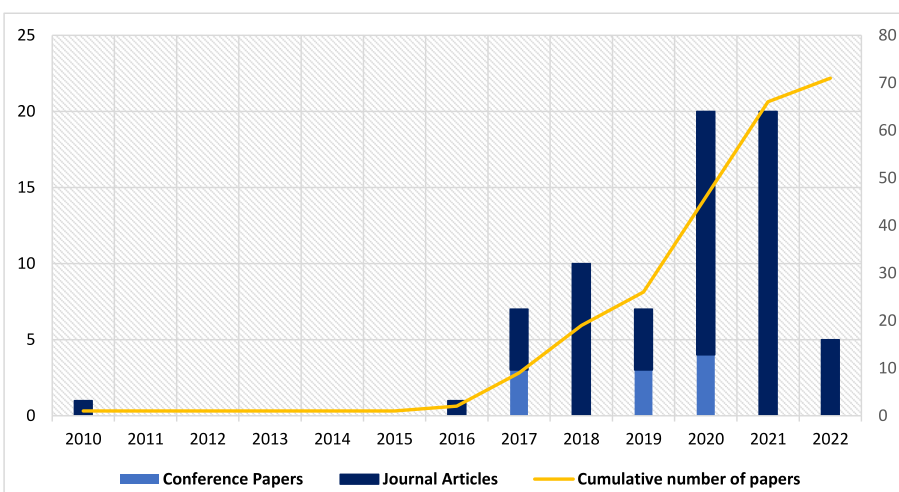

Fig. 2. Annual distribution of the article publications.

Akanbi et al. (2018) study focuses only on those three components, while CE aims to reuse or repurpose all components involved in the building. Xing et al. (2020) suggest the use of cloud-based cyber-physical data-sharing platforms enabling designers "to explore and identify reusable/reused components to assess their suitability for their building projects in comparing with other new products" (2020, p. 9). The data regarding the building components are collected through Radio Frequency Identification (RFID), processed through the BIM, and stored on the cloud; however, the technologies' development and subsequent use in the field are irregular (Xing et al., 2020). RFID technology has been increasingly adopted in the construction sector. For example, a case study in Australia demonstrated how RFID tags were used to track prefabricated concrete elements, resulting in the reduction of waste and around 15% increase in productivity (Moon et al., 2018). Singapore's Building and Construction Authority (BCA) (Annual Report, 2021) has paved a way for this in South East Asia where the use of RFID has been used to track and manage construction waste. Furthermore, a remarkable case study from the US demonstrates how RFID can be involved in a green/circular construction project where a building is designed for disassembly purposes. Material passports were developed using RFID tags, hence facilitating at the building's EoL, easy identification of every part that can be remade or recycled (Moreira et al., 2012).

Nevertheless, any knowledge regarding the location of the reusable building components and materials leading towards better reuse in the buildings EoL does inform design teams how better and more efficiently to design a circular building. Fig. 3 summarises the interaction of the built environment design stage in line with CE and digital transformation Principles.

4.2. The Life Cycle Assessment as a circularity tool

The Life Cycle Assessment (LCA) is regarded as a practical performance assessment methodology and tool analysing products environmental repercussions (Welling and Ryding, 2021), with the capacity to increase the built environment's circularity. The LCA in the construction industry is recognised as a method used to measure the environmental impacts of the whole building or the evaluation of specific building components (Fokaides et al., 2020). LCA tools such as GaBi and SimaPro, amongst others, are used to assess products' environmental impact and compile an inventory assessment. Anastasiades et al. (2020) argue that although already digitalised, the method should be simplified if it is to be used as an efficient tool for CE purposes. The standardisation of the buildings' LCA (Joensuu et al., 2020) and the incorporation of its tools into the BIM (Kovacic et al., 2020) could reduce the mentioned complexities. Kovacic et al. (2020) have found that databases used by LCA are region-based (i.e., America – BEES, Denmark – DBRI4, IO-Database – EU etc.), conforming with national standards, which are not necessarily circular and most certainly not universal, (Fig. 4).

Regarding a potential link between LCA tools and BIM, Akbarieh et al. (2020) find that the link currently takes a form of a plug-in. They state that "direct data exchange in BIM-LCA studies is not mature enough and these tools have remained disconnected so far" (Akbarieh et al., 2020, 12). Therefore, the fully automated interaction between BIM and LCA tools is yet to be developed (Dalla Valle, 2021a; Kovacic et al., 2020). Xue et al. (2021) highlight the importance of BIM-LCA integration in advancing CE of construction industry. They identified significant opportunities and challenges in merging BIM and LCA, particularly in terms of data management and interoperability. Opportunities lie in enhanced decision-making, sustainability, and efficiency in building designs. However, the challenges include managing complex data, ensuring technical interoperability between BIM and LCA tools, and standardizing methodologies.

Succar and Poirier (2020) advanced the *Lifecycle Information Transformation and Exchange* (LITE) framework, which is an "extendable conceptual skeletal for defining, managing, and integration project and asset information" (2020, 1). The LITE complete information loop would ensure data utilization from 'cradle to cradle', which could promote the CE principles at a larger scale. Creating an interface that links both BIM and LCA tools or developing a framework like LITE would enhance circular automatization in construction and subsequently increase the number of circular projects implemented (Fig. 4).

4.3. The digitalisation of stakeholders' collaboration and circular economy

The cooperation of all stakeholders at any stage of a building's lifecycle is contingent upon effective communication and collaboration. This is best achieved through the digitalisation of the relationship. Chiaroni et al. (2021) highlights the crucial role of digital technologies in circular building business model's transition. It delves into how digital technologies enhance circularity in building, exemplified through a building company's stakeholder collaboration platform, illustrating the contribution of digital technologies to the business model shift towards CE.

Fedoseeva (2020) argues that digitalisation fosters "dynamic cooperation by implementing constant information exchange of network

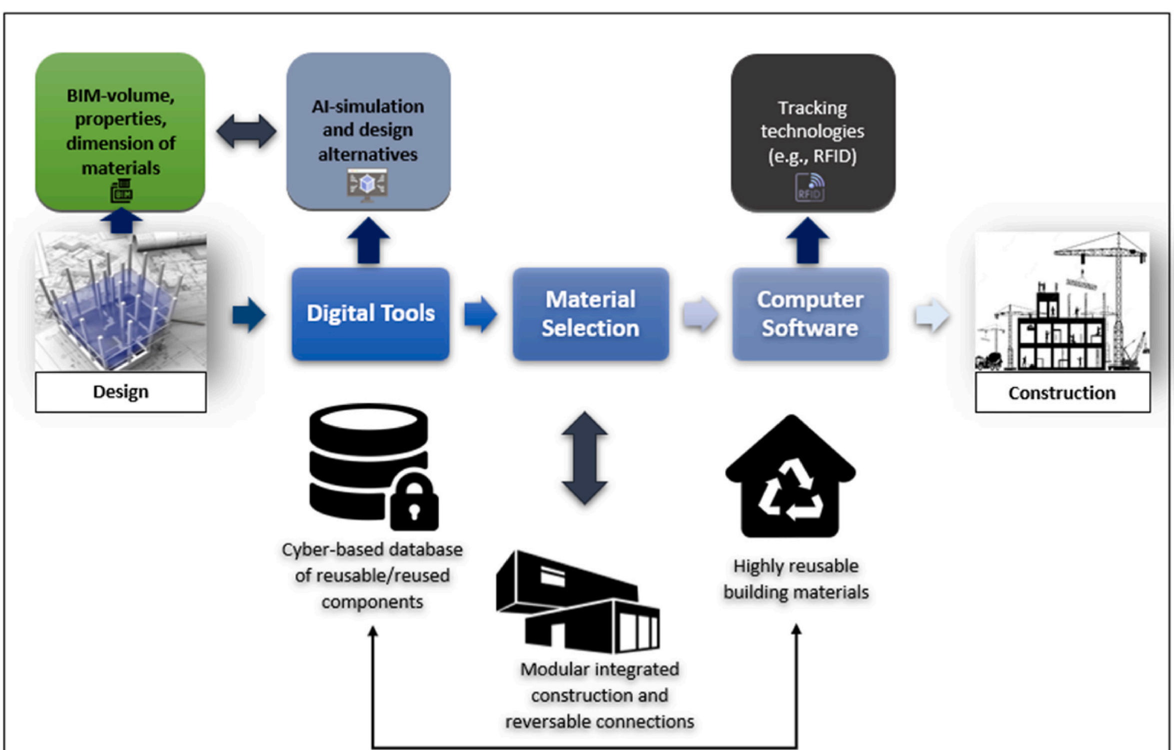

Fig. 3. The design stage in line with CE principles (adopted from Akanbi et al., 2018; Akbarieh et al., 2020; Antwi-Afari et al., 2021; Ernstsen et al., 2021 & Xing et al., 2020).

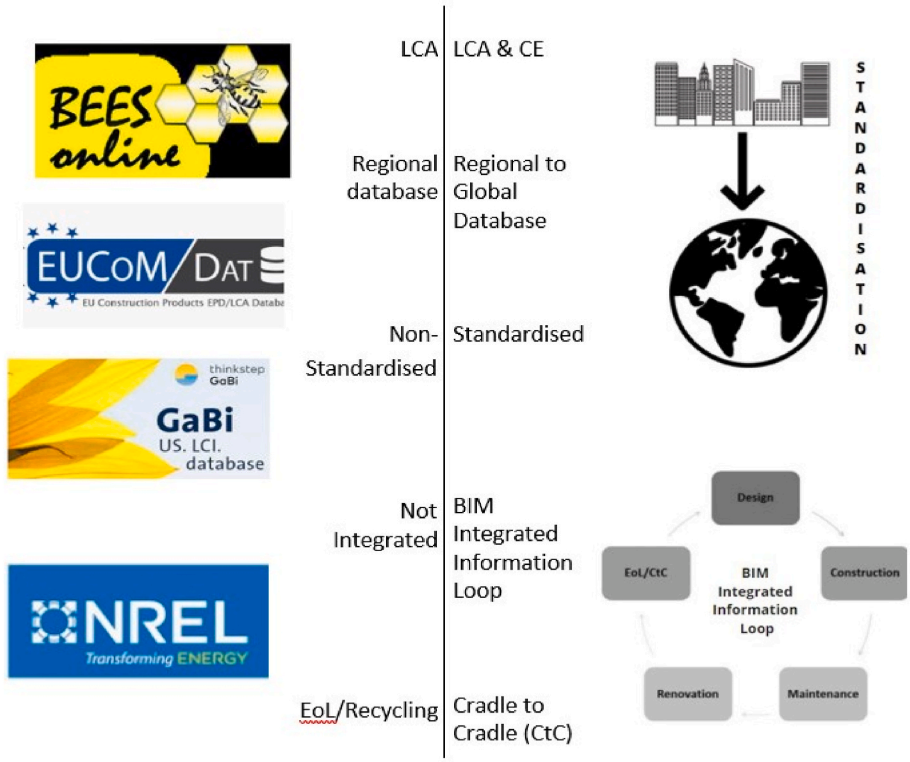

Fig. 4. LCA incorporating CE Principles (Adopted from Akbarieh et al., 2020; Fokaides et al., 2020; Kovacic et al., 2020; Naneva et al., 2020 & Succer and Porier, 2020).

members, coordinating the mutual exchange of resources or services, reducing paper document flow and response time to events (2020, p. 8). However, Chang and Hsieh (2019) find what is lacking in Taiwan's construction industry is the awareness of other stakeholders (i.e., manufacturing), thus, impeding the circularity of Taiwanese buildings. Having the stakeholders' collaboration in mind, Durmisevic et al. (2017) examined the reversible building design by examining the potential of material transferability. The software framework developed should portray a connector between all stakeholders at a building design stage, acting and providing "the optimum solution by offering immediate feedback to each design step" (Durmisevic et al., 2017, p. 265). The efficient collaboration between the manufacturers, suppliers, designers, engineers, builders and all other stakeholders involved leads towards efficient construction, and the collaboration, according to Ernstsen et al. (2021).

The digitalisation of the construction industry relationships also leads to a more significant problem and solution identification, i.e., standardisation and reduction in complexities (Ernstsen et al., 2021) and faster processes (Li et al., 2016). Li et al. (2016) propose the incorporation of *Distributed Ledger Technologies* or *Blockchain* with the shared-access BIM models, enabling all stakeholders to insert and update the information and thus streamlining the processes. Hence, a BIM handover should be developed to ease the transition (Cavka et al., 2018).

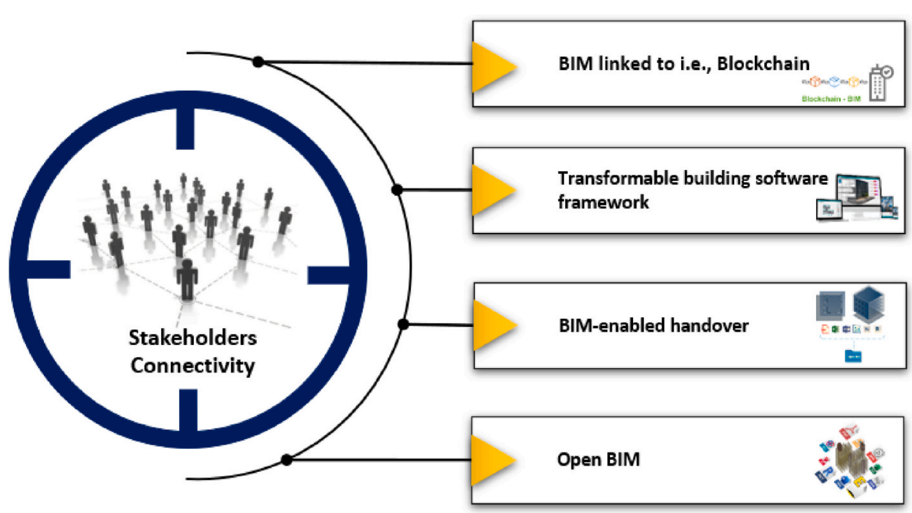

Fig. 5. Options for increased stakeholder connectivity (adopted from Akbarieh et al., 2020; Cavka et al., 2018; Durmisevic et al., 2017; Li et al., 2016 & Xing et al., 2020).

The examples above (Fig. 5) recommend either the creation of a new software framework (Durmisevic et al., 2017), linking two platforms (Li et al., 2016) or efficient handover (Akbarieh et al., 2020; Cavka et al., 2018). However, Xing et al. (2020) discuss using a cloud-based BIM System, allowing all stakeholders to exchange design information online and in real-time. The open sharing of the designs leads to their accessibility to more significant numbers of stakeholders. Likewise, Iyer-Raniga (2019) argues that should the designs become a part of an open-source, it would allow other stakeholders to review, reuse and build on the design. Oesterreich and Teuteberg (2016) find that 'cloud computing' eases the collaboration between various stakeholders involved in the construction project. It creates digital storage accessible by all (Ávila-Gutiérrez et al., 2020), thus allowing the greater circularity of the design, bringing it closer to the fruition of CE principles.

4.4. Circular construction – prefabrication, reversible connections and on-site manufacturing

The circularity of the industry could be drastically improved by rethinking the type of construction methods and means employed. Materials used and methods employed in the project are predetermined during the design stage but executed during the construction phase. Antwi-Afari et al. (2021) argue that using modular integrated construction and reversible connections combined with digital technologies is one path to achieving circularity. Selecting adequate construction materials, such as prefabricated building components, could lead towards a more circular construction industry and faster, more efficient, and safer onsite work. In addition, prefabricated components, due to their standardised sizes, accommodate for subsequent reuses (Akbarieh et al., 2020; Xing et al., 2020), ensure a reduction in onsite waste as none to minor modification is needed (Esa et al., 2016; Iyer-Raniga, 2019; Osterreich and Teuteberg, 2016).

Additionally, it exhibits water and energy savings as hours are spent on the project, wet construction is reduced (Esa et al., 2016; Iyer-Raniga, 2019), and prefabricated components are easily disassembled (Xing et al., 2020). The disassembly at the EoL stage is probably the most important attribute here. Nazareth (2019) examined the potential for reusability of the fully modular *Deen Street* building and concluded that stakeholders had made maximum possible reuse by using prefabricated components. However, applying prefabricated components is not new in the building industry, and yet, reuse was not always given in modular construction. The reuse of the modular building components can be eased with the technology.

The digital transformation has enabled the greater circularity of the prefabricated building components. Li et al. (2016) proposes an RFID-enabled BIM platform (RBIMP) to mitigate risks and improve stakeholder communication. The RFID chips, integrated into the prefabricated components, connect the physical element and virtual data (Antwi-Afari et al., 2021). Kedir and Hall (2021) highlighted the potential of RFID technology as a tool for material management,

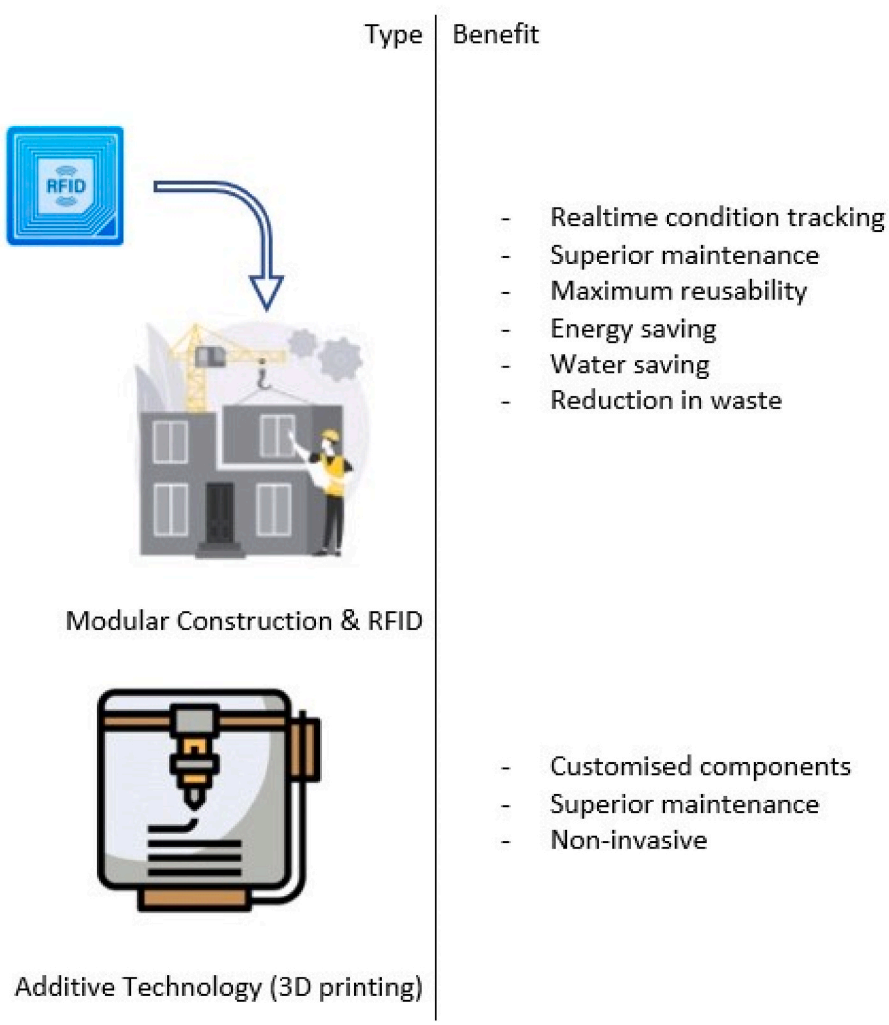

Fig. 6. Technology supporting CE at the construction stage (adopted from Akbarieh et al., 2020; Antwi-Afari et al., 2021; Esa et al., 2017; Iyer-Raniga, 2019; Kedir and Hall, 2021; Li et al., 2016; Osterreich and Teuteberg, 2016; Xing et al., 2020).

potentially extending the component's lifecycle through adequate maintenance. The maintenance aspect is raised by Anastasiades et al. (2020) in their discussion regarding *shearing layers*. That is, the identification of the building components that age at a different pace allows these components to be repaired or replaced as per information collected with RFID chips and BIM available inventory. However, Li et al. (2016) state that BIM is often used by the stakeholders belonging to the construction industry. Akbarieh et al. (2020) suggest that data collected through the RFIDs could be stored in the Open BIM platform, thus, making the reuse accessible to a more significant number of stakeholders. However, Xing et al. (2020) argue that the cloud-based system's effectiveness for CE is contingent on the improved prefabrication of components with disassembly and reuse in mind. Also, RFID monitoring of building components is mainly used for construction purposes and updating the supply chain (Xing et al., 2020), thus promoting the material loop (Fig. 6).

Furthermore, as the material loop is prioritised in CE, it is best practised through the joints designed to be easily dismantled. The DfD advocates for the non-permanency of building components; thus, easily removable building elements are prioritised and ensure straightforward maintenance and disassembly. In the same vein, Kedir and Hall (2021) argue that if the connection between components is invasive and not removable (i.e., nails rather than screws), the building components could be damaged during the assembly and rendered unusable in the EoL stage. Many of these joining building components are ready-made by the manufacturer; however, in some more complex architectural designs, technology such as additive manufacturing can be applied to make components onsite. Oesterreich and Teuteberg (2016) state that additive manufacturing technology, based on a 3D printing digital model, can create onsite complex building components without extra labour costs. Additive manufacturing is seen as one of the enablers of the CE. It not only supports customised manufacturing, but additive manufacturing also improves the lifecycle management of products (Rosa et al., 2020). It thus maintains the quality of the building stock, which forms an integral part of the material passports (Fig. 6).

4.5. Material passports and material banks

Material passports are composed from building components data and characteristics which facilitate greater reusability and simultaneously incentivise the supply of "healthy, sustainable and circular materials/ building products" (BAMB, 2016). Material passports are either created at the design phase (Nazareth, 2019) and updated throughout the maintenance stage (Kovacic et al., 2020) or by using the technology to identify the materials used in buildings before the data digitalisation. Kedir and Hall (2021) argue that already existing BIM inventarisation of the materials used for the construction could serve as a material passport for the individual components, feeding into the material banks. However, to ensure the greatest circularity of the building materials, transparency in the design, construction and maintenance must be observed (Iyer-Raniga, 2019). The material passport ought to possess information regarding components of "lifecycle, reuse strategies and recycling outlets" (Antwi-Afari et al., 2021, p. 9) to viably contribute towards the building circularity. Antwi-Afari et al. (2021) note that incorporating RFID chips and their integration with BIM through an online and cloud-based framework ensures a real-time update of the material passport supporting the second-hand material markets. Utilizing cyber-physical systems leads to better lifecycle management (Rosa et al., 2020). The further augmentation of the real-time frameworks could be achieved by the frequent use and interconnection of other digital platforms, such as "digital twin, machine learning, virtual reality and internet of thing (IOT)", These could enhance material identification and data storage (Antwi-Afari et al., 2021), as well the reduction of reliance on virgin materials (Nasiri et al., 2017). The data collected with the RFID technology provides invaluable insight into how the product was used and its current condition, but it is not the only technique (Fig. 7).

The applied gamification-based concept is another method that could be used in updating the BIM-created digital twin of the building. The gamification process is the application of computer games and virtual reality and augmented reality tools which are characterised by decreased inhibition processes and increased motivation to participate in efficient user-BIM collaboration (Pütz et al., 2020). Gamification is particularly popular as a game that directly exhibits the impact of the actions (Santti et al., 2019), stimulating the input of user-dependent data. For example, a user would take an image of a section of the building and upload it to the BIM gamification platform, directly inserting the data and providing valuable feedback on the condition of the building or recording any building modification (Kovacic et al., 2020). However, gamification could only serve as one way of updating material passports, as the user reliance is unpredictable. Monitoring material conditions through intelligent sensor systems could assist (Liu et al., 2021). Still, technology is currently reserved for intelligent homes and introduced towards smart cities, far from contributing significantly

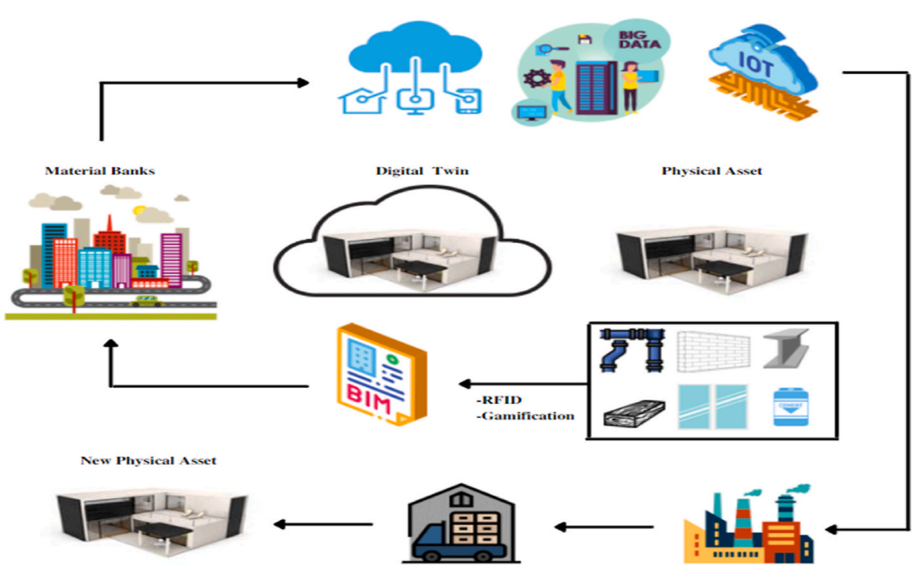

Fig. 7. The Material passport and material banks management through cloud-based digital technologies (adapted from Antwi-Afari et al., 2021; Gutiérrez et al., 2020; Kovacic et al., 2020; Minunno et al., 2018; Nazareth, 2019; Oesterreich and Teuteberg, 2016; Xing et al., 2020).

towards material passport updates and CE (Fig. 7).

The automatic update of material passports and real-time building component condition review could achieve its maximum benefit if it were deemed easily accessible by all interested stakeholders in the form of digital material banks. Minunno et al. (2018, 125) proposed "storing the information of every component of a building", conceptualising cities as material banks, thus, creating a new supply chain. Similarly, Xing et al. (2020) promote the benefit of the cloud-based BIM prototype as a potential supply chain of reusable materials. The platform is designed to support the workflow between clients (i.e., building designers) and suppliers (i.e., manufacturers). The information update depends on the RFID tags, directly communicating components data to the BIM-generated digital twin through the seamless information exchange via the cloud (Antwi-Afari et al., 2021). Progressively, Mêda et al. (2021) presents an advanced analysis of digital twin technologies and delves into Digital Data Templates, Digital Building Logbooks, and Digital Twin Construction, emphasizing their potential for enhancing CE of construction. The research is significant in clarifying the interrelations and synergies among these digital concepts, proposing an integrated, data-driven framework for promoting CE and resource efficiency.

Oesterreich and Teuteberg (2016), not discussing CE *per se*, found that using cloud-based *Big Data* in construction could identify risky patterns or improve the decision-making process. Arguably, such technology could also instigate the change process (Manfren et al., 2021) and bring the construction industry closer to sustainability (Ernstsen et al., 2021; Esetova et al., 2019) if data regarding building components are processed and used accordingly. However, Ávila-Gutiérrez et al. (2020) propose using local clouds created with the Arrowhead architecture highlighting potential issues with security and scalability of cloud interaction. Creating local clouds is good from a cost-cutting and time-saving perspective, as the locally and easily accessible/reusable materials and suppliers align with the circular approach. However, the localisation of material banks versus creating a national database could diminish the number of opportunities, as materials would not be adequately reused; the promotion would be limited to local construction projects (Fig. 7).

4.6. From "End of Life" to "cradle to cradle"

Newer constructions benefit from their already existing BIM-based material passports and digital twins; however, older buildings do not. The potential of reusability for the building components of existing buildings is often unknown; hence the reason for CDW is an extensive problem. The CDW accounts for approximately 30% of all solid wastes generated globally (Robayo-Salazar et al., 2020). The need to reuse, repurpose or recycle, even downcycle the CDW, is pressing. The greater reusability of the older building components is achievable through the subsequent digitalisation of the building's design and the creation of material inventory. Nazareth (2019) argues that laser technology could scan older structures, creating a BIM 3D image of the building, which forms an integral part of the *Asset Information Model*. The UK supermarket chain *Sainsbury* has digitalised all their existing 2D assets blueprints based on BIM standards, making them accessible as *digital assets* through their Common Data Environment (PCSG, 2018). Likewise, Volk et al. (2018) developed the *ResourceApp*, a system consisting of "a sensor and algorithms for data processing that allows data acquisition and registration, object detection, analysing and optimised project planning for building deconstruction projects" (2018, p. 242). The system allows for the subsequent creation of buildings' 3D modules or digital twins and maps the materials forming the part of the structure. Although Akbarieh et al. (2020) argued that digitalisation had eased the pathway towards the reuse of building materials, there is yet to be a universally accepted BIM-based EoL solution. This could relate to the purpose of the older building's digitalisation and is rarely the material recovery but rather the renovation and maintenance of the structure. Furthermore, EoL frameworks are not a part of commercially available BIM options but are rather subsequently added by stakeholders if circularity is considered. Adding tools is an option; however, Akinade et al. (2020) found that the "major limitation of existing end-of-life waste analytics and DfD tools is that they are not BIM compliant" (Akbarieh et al., 2020) (Fig. 8).

The identification of the reusable components is better to be made before buildings demolition; however, as most structures today do not have their digitalised material passports, nor is the CE business model widespread in built environment, most building components end up as a part of the CDW. Huang et al. (2018) study conclude that otherwise, reusable building components often end up in landfills because of the contaminations caused by the demolition. Sorting through the CDW is an option, either done at the site or an alternative location (Lopez Ruiz et al., 2020). With this respect, Oesterreich and Teuteberg (2016) argue that robotic hardware could be used to shift through CDW and separate reusable, recyclable or down-cyclable components. However, shifting through the debris is nearly impossible without easily accessible knowledge of the actual components of the demolished structure. The information is essential firstly, to maximise the materials extraction and secondly, to avoid potentially toxic components. Hence, creating the BIM model, either through laser scanning or digitalisation of the 2D blueprints, should be a priority for minimising and eventually eliminating CDW in older structures (Fig. 8).

5. Thematical and gap analysis

5.1. Research themes

The dominant theme of the examined literature was drawn from an intensive and critical examination of 36 highly relevant publications. Table 3 narrows three dominant directions on CE, built environment and digital transformation where either two required concepts were extensively discussed, while the third was sporadically addressed, or all three components were present. A few studies examine the CE aspects through the digital transformation of the built environment such as (Çetin et al., 2021; Çetin et al., 2022); however, the dominant themes vary. Most of the literature leans towards the development of an online open database (OpenBIM, BAMB, etc.) which could ensure greater stakeholder connectivity and maximum reusability of the building components (Ávila-Gutiérrez et al., 2020; Della-Valle, 2021; Fokaides et al., 2020; Garcia-Muiña et al., 2018; Gepts et al., 2019; Joensuu et al., 2020; Kovacic et al., 2020; Li et al., 2016; Liu et al., 2021; Oesterreich and Teuteberg, 2016; Prakash and Ambekar, 2020; & Xing et al., 2020). The second most dominant topic is the incorporation of EoL tools at the design stage, subsequently resulting in CDW reduction (Akbarieh et al., 2020; Akinade et al., 2017; Akinade et al., 2020; Anastasiades et al., 2020; Durmisevic et al., 2017; Esa et al., 2017; Kedir and Hall, 2021; Minunno et al., 2018 & Nazareth, 2019). Some works highlight the importance of circular design in their discussion of buildings EoL (Akbarieh et al., 2020; Akinade et al., 2017; Akinade et al., 2020; Anastasiades et al., 2020; Chang and Hsieh, 2019; Durmisevic et al., 2017; Hodorog et al., 2021 & Nazareth, 2019) (Table 3). One work (Rahla et al., 2021) is focused on CE in built environment however, presenting practical case studies via the implementation of sustainable resource management, innovative design techniques, and the use of digital technologies; BIM and Material Passports. This study serves as real-world examples of how CE principles can be effectively translated from theory into practice.

All in all, these dominant themes interconnect, thus addressing every building stage in one form or another. However, the low number of publications points in the direction of neglect.

6. Lifecycle perspective in digitally-integrated circular construction

The integration of CE principles within the built environment is a

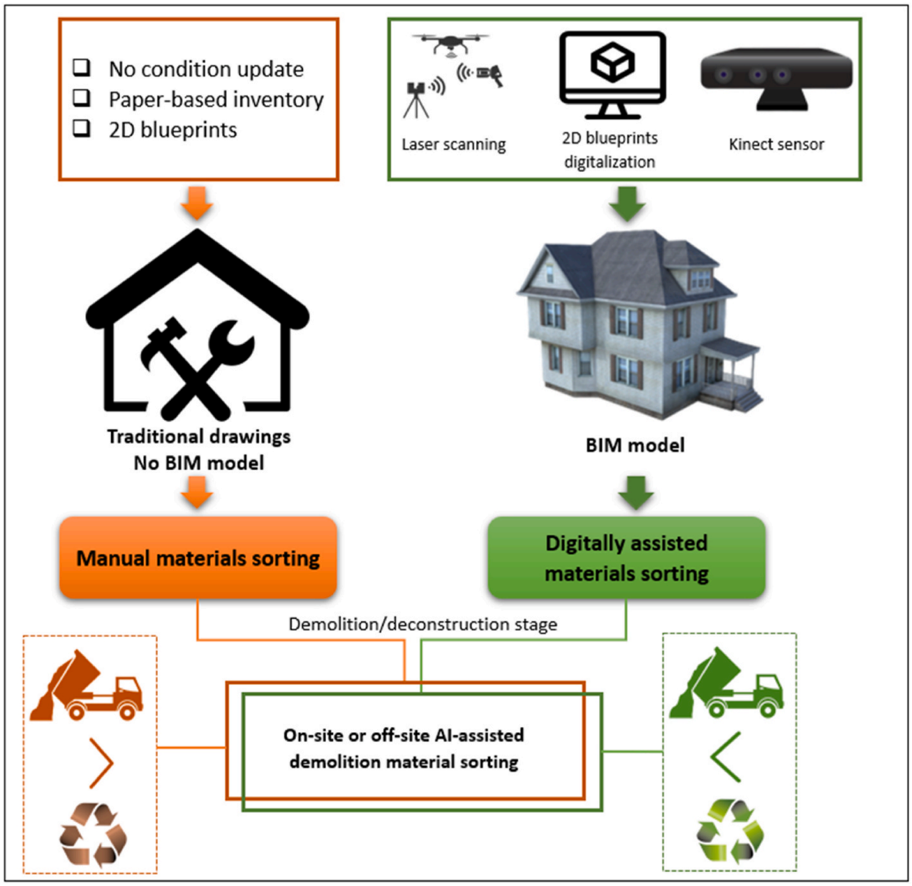

Fig. 8. The EoL reuse flow of the material components in existing buildings (adapted from Nazareth, 2019; Oesterreich and Teuteberg, 2016; PCSG, 2018 & Volk et al., 2018).

multi-faceted endeavour that intersects with various stages of a building's lifecycle. Digital technologies play a pivotal role in this integration, offering innovative solutions that enhance sustainability and resource efficiency from the design phase through to deconstruction (Zhang et al., 2023). This section delves into the lifecycle stages, providing a granular view of how digital integration fosters circularity in construction.

6.1. Design stage

The design stage is critical for embedding CE principles, with digital tools enabling architects and engineers to envision structures that are resource-efficient and adaptable to future uses (Ferdosi et al., 2022). For instance, a study by Aghasizadeh et al. (2022) illustrates how BIM facilitates the integration of 'design for disassembly' (DfD) principles, allowing for the anticipation of future material recovery and reuse (Aghasizadeh et al., 2022). Moreover, BIM's capacity to simulate material life cycles aids in selecting materials with lower environmental footprints, as explored by Banihashemi et al. (2022).

6.2. Construction stage

During construction, digitalisation ensures precise tracking and management of materials. The use of RFID technology, as detailed by Lu et al. (2011), allows for real-time tracking of material flow, reducing waste and enhancing the potential for material reuse post-deconstruction. Furthermore, the concept of material passports, which store data on the composition and quality of materials, facilitates the eventual re-entry of these materials into the supply chain, as advocated by Munaro and Tavares (2021).

6.3. Operation stage

In the operational phase, digital twins and smart sensors provide ongoing data that can be used to optimize building performance and extend the lifespan of materials and components. A case study by Motawa and Almarshad (2013) demonstrates how a digital twin model can predict maintenance needs, thereby preventing premature material wastage.

6.4. End-of-life stage

At the EoL stage, digital tools support the systematic deconstruction and sorting of materials. The concept of 'urban mining', facilitated by digital inventories of building materials, is exemplified in the work of Cheshire (2019), who discusses how such platforms can enable the recovery and redistribution of valuable construction resources.

6.5. Cross-Lifecycle Integration

The seamless integration of CE principles across the building lifecycle necessitates a holistic approach, where digital tools are employed not in isolation but as part of an interconnected system. The 'material bank' concept, as proposed by Braungart and McDonough (2009), is predicated on the idea of materials being tracked and managed through digital means from inception to reuse, ensuring a closed-loop system that maximizes resource efficiency. By adopting a lifecycle perspective, it becomes evident that digital technologies are not merely facilitative but transformative, enabling a paradigm shift towards a more circular and sustainable construction industry (Banihashemi and Zarepour Sohi, 2022). Çetin et al. (2021) presents a novel lifecycle-phased framework

Table 3
Identified themes.

No.	Reference	CE & BE – sporadically discussing DT	DT & BE – sporadically discussing CE	DT, BE & CE
1	Akbarieh et al. (2020)			✓
2	Akinade et al. (2017)			✓
3	Akinade et al. (2020)			✓
4	Anastasiades et al. (2020)	✓		
5	Anwi-Afar et al. (2020)	✓		
6	Ávila-Gutiérrez et al. (2020)			✓
7	Chang and Hsieh (2019)			✓
8	Cavka et al. (2018)			✓
9	Çetin et al. (2021)			✓
10	Çetin et al. (2022)			✓
11	Chiaroni et al. (2021)			✓
12	Cramer (2023)			✓
13	Della-Valle (2021)		✓	
14	Durmisevic et al. (2017)			✓
15	Ernstsen et al. (2021)		✓	
16	Esa et al. (2017)	✓		
17	Fokaides et al. (2020)			✓
18	Garcia- Muina et al. (2018)			✓
19	Gepts et al. (2019)			✓
20	Hodorog et al. (2021)			✓
21	Iyer-Raniga (2019)	✓		
22	Joensuu et al. (2020)			✓
23	Kedir and Hall (2021)	✓		
24	Kovacic et al. (2020)			✓
25	Li et al. (2016)			✓
26	Liu et al. (2021)			✓
27	Mêda et al. (2021)			✓
28	Minunno et al. (2018)	✓		
29	Nazareth (2019)			✓
30	Naneva et al. (2020)		✓	
31	Oesterreich and Teuteberg (2016)		✓	
32	Olanrewaju et al. (2021)		✓	
33	Prakash and Ambekar (2020)		✓	
34	Rahla et al. (2021)	✓		
35	Xing et al. (2020)			✓
36	Xue et al. (2021)			✓

to guide the integration of digital technologies in fostering a circular economy within the built environment. It systematically maps out ten key digital technologies, including additive/robotic manufacturing, AI, big data, BIM, digital twin, material passports, blockchain, digital platforms/marketplaces, the geographical information system, and IoT, and links them to circular building strategies across various lifecycle stages. This work is a significant step in understanding and enhancing the role of digitalisation in achieving sustainable and circular practices in construction and built environment management. However, it can be inferred that the article offers a structured framework linking specific digital technologies to circular strategies, while the present study focuses more on the challenges and the need for strategic approaches, towards the lifecycle perspective.

As another and most recent effort, Liu et al. (2022) offers a systematic literature review to identify digital functions supporting CE strategies. It identifies 13 critical digital functions including Traceability, Transparency, Visibility, Accessibility, Connectivity, Interoperability, Decentralization, Intelligence, Scalability, Security, Reliability, Efficiency and Sustainability. It proposes a framework to illustrate how these functions can be applied across different CE strategies. However, this study provides a broader, more systematic categorization and framework of digital functions applicable to CE strategies. It is neither focused on the built environment and practical challenges of this sector, nor presenting a stage-wise development and perspective.

The literature provides a wealth of examples that not only demonstrate the practical application of these digital tools but also underscore the importance of continued innovation and research in this domain.

6.6. *Gap analysis*

The neglect as a gap revolves around the general lack of comprehensive discussion on how digital transformation could incorporate CE principles within the built environment. The literature acknowledges the importance of CE for the construction industry and elaborates on generalised methods which could be achieved. However, the discussion is narrowed and sporadically examined when it is linked to the digital transformation. Ernstsen et al. (2021) explore the relevance of digital transformation, studying three visions of "efficient construction, user-data-driven built environment and value-driven computational design." Efficiency, an essential contribution of digital transformation, should ensure that digital aspects are included when discussing circular buildings. The current literature, with some exceptions, has a narrow focus. The tailored discussion is understandable as the scope of the research predetermines its feasibility. However, as stated earlier, incorporating CE principles within the built environment through the digital transformation is not a clear-cut sectioned endeavour. It is a series of interrelated stages where decisions made at one impact the circularity of the processes at the others (i.e., gamification at the maintenance stage leads towards greater reusability of the building components).

Furthermore, creating a digital inventory of buildings constructed prior to using digital tools is insufficiently discussed. Using the determined parameters, the literature search has only resulted in three works which examine the potential and solution for the digitalisation of older structures (Nazareth, 2019; Oesterreich and Teuteberg, 2016; Volk et al., 2018). As most of the buildings standing today were constructed before the digital transformation of the built environment, there should be a degree of urgency to digitalise or develop technologies that could assist with the digitalisation process.

Further gap lies where the trend necessitates more than technological advancements. Digital technologies enhance CE practices by visualizing environmental impacts along the value chain and improving design and material efficiency. However, achieving these benefits requires systemic changes in institutions, behaviour, and socio-economic factors. Cramer (2023) asserts that network governance, complementing traditional public governance, can promote collaborative efforts for systemic change, fostering a new CE paradigm and regulatory innovation. This governance's effectiveness varies with the socio-cultural and political context and should be addressed according to the different economic, social and environmental priorities.

7. Structured conclusion

7.1. *Aim and methodology*

The study aimed to critically review the literature on the role of digital transformation in integrating Circular Economy (CE) principles within the built environment. A systematic analysis was conducted to discern how digitalisation intersects with the various stages of a building's lifecycle.

7.2. Key findings

- Lifecycle Integration: Digitalisation is identified as a crucial element across all stages of the building lifecycle, with a particular emphasis on design and construction in the contemporary context where 3D designs and digital twins are prevalent.
- Applicability to Existing Structures: The study acknowledges the gap in applying digital transformation to existing structures, highlighting the potential of technologies like 2D blueprint digitalisation and laser scanning for material reuse.
- Efficiency and CE Tools: The research underscores the efficiency gains from digital transformation in construction processes and suggests that embedding CE tools could further enhance these benefits.

7.3. Future research directions

- Localized material banks: The need for further research into localized material banks and the implications of open-source access on circularity.
- RFID utilization: An exploration of RFID tag usage and its impact on circularity in both new and existing buildings.
- Design for Disassembly (DfD): An examination of DfD tool adoption in new building designs and the factors influencing their use.
- Digital inventory of older structures: An investigation into the methods and extent of creating digital inventories for older buildings, and the regional factors affecting digitalisation.
- Circularity of LCA databases: An assessment of the circular nature of LCA databases and their integration with BIM.
- Policy and CE: A study on the current policies affecting CE in construction and the potential for these policies to drive future circularity in the industry.

7.4. Practical implications

The findings from this study have significant implications for the construction industry, suggesting that digital transformation could be a catalyst for embedding circularity. However, the transition requires supportive policies and industry-wide collaboration to ensure the supply of reusable materials and the promotion of circular designs.

1) Lifecycle Integration and Efficiency:
   - Design and Construction: The adoption of digital tools like BIM and digital twins streamlines the design and construction process, leading to reduced waste and more efficient resource use. This results in cost savings and shorter project timelines.
   - Retrofitting and Renovation: For existing structures, digital inventories and the use of technologies such as 3D scanning facilitates the identification of materials for reuse or recycling, contributing to the reduction of demolition waste.
2) Localized Material Banks:
   - Resource Optimization: The development of localized material banks optimizes the use of resources by promoting the reuse of building materials within a specific region, reducing transportation costs and environmental impact.
   - Economic Development: These banks can stimulate local economies by creating new markets for reclaimed materials and fostering innovation in material recovery and recycling processes.
3) RFID and Material Traceability:
   - Asset Management: Implementing RFID technology enhances asset management by providing accurate data on material location, condition, and history, thus facilitating maintenance and eventual material recovery.
   - Regulatory Compliance: RFID can also assist in meeting regulatory requirements for material traceability and waste management, potentially reducing legal risks and enhancing the industry's reputation.
4) Design for Disassembly (DfD):
   - End-of-Life Value: Buildings designed for disassembly retains more value at the end of their life, as components can be easily dismantled and reused, reducing the need for new materials and the associated environmental footprint.
   - Innovation in Design: DfD encourages innovation in design practices, leading to buildings that are not only more sustainable but also adaptable to future uses, extending their lifespan.
5) Circular LCA Databases:
   - Informed Decision-Making: Integrating circular LCA databases with BIM aids architects and engineers in making more informed decisions about materials and construction methods that minimize environmental impacts.
   - Standardization and Benchmarking: Circular LCA databases can serve as a benchmark for sustainability standards, helping the industry to measure and improve its performance over time.
6) Policy Influence on Circular Economy:
   - Guidance and Incentives: Clear policies can guide the construction industry towards circular practices by setting standards and providing incentives for the adoption of circular principles.
   - Public Awareness: Policies can also play a role in raising public awareness about the benefits of circular construction, driving demand for buildings that are designed and built with sustainability in mind.

8. Concluding remarks

While digital transformation holds promise for advancing circularity in construction, the industry's readiness varies, and there is a need for a unified approach to fully realize the potential benefits. This study lays the groundwork for future research leading to a more sustainable and circular built environment. The practical implications of this study's findings offer a roadmap for industry stakeholders to follow as they seek to implement these changes in the real world.

CRediT authorship contribution statement

Saeed Banihashemi: Conceptualization, Funding acquisition, Project administration, Supervision, Formal analysis, Methodology, Writing – review & editing. **Senada Meskin:** Formal analysis, Writing – original draft, Data curation. **Moslem Sheikhkhoshkar:** Data curation, Methodology, Visualization. **Saeed Reza Mohandes:** Validation, Visualization, Writing – review & editing. **Aso Hajirasouli:** Validation, Visualization, Writing – review & editing. **Khuong LeNguyen:** Validation, Visualization, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT/ScholarAI tool in order to improve the language and readability of the paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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