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Citation for published version:
Long, W, Ng, ST, Lu, W, Mora, L & Bao, Z 2025, 'Deciphering how digital functions enable circular economy practices in construction: A critical review of recent progress and future outlook', *Environmental Impact Assessment Review*, vol. 113, 107889. https://doi.org/10.1016/j.eiar.2025.107889

Digital Object Identifier (DOI):
10.1016/j.eiar.2025.107889

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Publisher's PDF, also known as Version of record

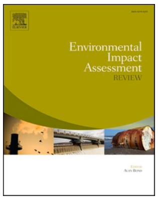
Published In:
Environmental Impact Assessment Review

Environmental Impact Assessment Review 113 (2025) 107889

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar



Deciphering how digital functions enable circular economy practices in construction: A critical review of recent progress and future outlook

Wuyan Long [a], S. Thomas Ng [b], Weisheng Lu [c], Luca Mora [d], Zhikang Bao [e,*]

[a] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Hong Kong
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong
[c] Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Pokfulam, Hong Kong
[d] Business School, Edinburgh Napier University, Edinburgh, UK
[e] School of Energy, Geoscience, Infrastructure, and Society, Heriot-Watt University, Edinburgh, UK

ARTICLE INFO

Keywords:
Digitalization
Digital functions
Circular economy
Construction industry
Critical review

ABSTRACT

The growing interest in leveraging digital technologies to advance circular economy practices in construction reflects the global push for Industry 4.0 and sustainable development. However, a comprehensive understanding of how digital technologies can effectively support circular initiatives in the sector remains limited. This study addresses this gap by critically reviewing the role of digitalization in enabling circular strategies through an innovative academic lens, exploring a more refined and sophisticated mechanism in which digital technologies are decomposed into their corresponding digital functions. Through a thorough analysis of 125 papers, 10 digital functions and 15 circular strategies in construction have been unveiled. By correlating these functions with strategies in an organized framework, it was found that different functions are typically supported by specific digital technologies. Among the most frequently emphasized functions are “assess”, “auto-plan”, “collect”, and “estimate”. The reliance on digital functions varies across different circular economy strategies. This study also highlights three key research gaps for future exploration: (1) the application of digital technologies in under-explored lifecycle stages, with a particular focus on strategies for extending building lifespan, (2) reuse and recycling practices at the meso- and macro-scales, and (3) the development of robust data management mechanisms. By offering insights into the state-of-the-art of existing research, and unexplored areas deserving future investigations, this study aids in propelling the conversation on digitalization-enabled circular construction practices.

1. Introduction

The construction industry is crucial to global prosperity, contributing 13 % to Gross Domestic Product and 7 % of global employment (Elghaish et al., 2022). However, it is also one of the most environmentally harmful sectors, responsible for one-third of carbon emissions, two-fifths of raw material consumption, and two-fifths of solid waste production (Gao et al., 2024; van der Zwaag et al., 2023). These impacts arise not only from the inherent characteristics of construction (e.g., large-scale and heavy materials) but also from inefficient resource use (Al-Hamrani et al., 2021; Migliore et al., 2020). The industry remains largely governed by a linear economy model, which begins with extraction, production, and use, and ends with the disposal of construction materials as waste in landfills. This model exposes stakeholders—including contractors, clients, and supply chain professionals—to risks such as rising resource costs and supply chain disruptions (Elghaish et al., 2022). To significantly reduce its environmental footprint, a shift from the linear to the circular economy model is essential for the construction industry.

Over the last decade, the concept of the circular economy has gained significant attention from governments, organizations, and academics as a potential pathway to enhance resource efficiency and achieve carbon neutrality in the construction sector (Ness and Xing, 2017; Bao et al., 2019). By adopting the circular economy model, greater value can be extracted from resources while minimizing material throughput (Besklubova et al., 2023; Bao, 2023). In the construction sector, the

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* Corresponding author.
E-mail addresses: wuyan.long@connect.polyu.hk (W. Long), thomasng@cityu.edu.hk (S.T. Ng), wilsonlu@hku.hk (W. Lu), l.mora@napier.ac.uk (L. Mora), zhikang.bao@hw.ac.uk (Z. Bao).

https://doi.org/10.1016/j.eiar.2025.107889
Received 21 November 2024; Received in revised form 11 February 2025; Accepted 23 February 2025

circular economy aims to preserve the intrinsic value of building components and materials over an extended lifespan. This approach promotes a continuous cycle of using, reusing, repairing, and recycling construction materials, thereby reducing construction and demolition waste (CDW) and mitigating environmental impacts, including CO_2 emissions (Akhimien et al., 2021). While large-scale implementation of the circular economy in construction is still in its early stages, several countries have already begun enacting policies to support its adoption. For example, Japan introduced “The Law for the Promotion of the Circular Economy” in 2008 to foster circular practices within the construction sector (Elghaish et al., 2022). Similarly, the European Union developed “CEN/TC 350/SC 1 – Circular Economy in the Construction Sector” to ground circular initiatives in practice (Rodrigo et al., 2024). However, to fully enable the industry’s transition to a circular economy, there is a consensus that further technological advancements are essential (Osei-Tutu et al., 2023).

A range of emerging digital technologies has significantly impacted the construction sector (Maskuriy et al., 2019), offering numerous opportunities to digitize the industry throughout its lifecycle and deliver substantial benefits (Çetin et al., 2021). These technologies enable more efficient management of construction materials during the design phase and optimize design, construction, and operation processes, thereby promoting reuse, repair, reconstruction, and recycling efforts (Talla and McIlwaine, 2024). In recent years, there has been growing interest in leveraging digital technologies to drive the transition of the construction sector from a linear to a circular business model. For instance, previous research highlights the potential of Building Information Modeling (BIM) to reduce CDW generation at the end-of-life phase, assess material circularity within the construction industry, and create material passports (Rodrigo et al., 2024).

Despite growing interest, a clear understanding of how digital technologies can be effectively leveraged to implement circular construction remains limited (Liu et al., 2022). Existing review studies on digitalization and circular construction can be broadly categorized into three areas: (1) exploring the potential of individual digital technologies or tools, such as BIM (Charef, 2022), Artificial Intelligence (AI) (Oluleye et al., 2023), and information and communication technology-based decision support tools (Yu et al., 2022a), to promote circular construction; (2) focusing on single circular economy scenarios, such as CDW management (Iyiola et al., 2024; Talla and McIlwaine, 2024); and (3) conducting comprehensive reviews of multiple digital technologies and circular economy scenarios (Çetin et al., 2021; Setaki and van Timmeren, 2022). However, existing reviews of multiple technologies and scenarios primarily focus on summarizing application examples, making it unclear how digital technologies implement circular strategies through their specific functions (Banihashemi et al., 2024; Rodrigo et al., 2024). Furthermore, research on whether specific digital technologies or their functions are preferred in particular circular construction scenarios remains limited (Setaki and van Timmeren, 2022). Given that each digital technology can support multiple functions, understanding the mechanisms that enable these functions is essential for advancing circular practices. Therefore, this study aims to investigate the digital functions enabled by specific digital technologies and the mechanisms underlying their effectiveness, offering insights to support the construction industry in adopting circular strategies through a systematic literature review.

The remainder of this paper is organized as follows: following the introduction, Section 2 outlines the definition and scope of the review study. Section 3 introduces the research methodology, while the review results are presented in Section 4. Section 5 provides a detailed discussion, and Section 6 offers the paper’s conclusion.

2. Definition and scope

2.1. Circular economy

The circular economy, an emerging model of economic development, aims not only to mitigate the environmental impacts of the traditional linear economy but also to drive a systemic shift toward a sustainable and regenerative production system. Drawing on diverse concepts such as industrial symbiosis, industrial ecology, cradle-to-cradle, and reverse logistics (Nobre and Tavares, 2021; Wuni, 2023), the circular economy seeks to optimize resource use, reduce waste, and minimize energy loss through efficient management and closed-loop systems (Geissdoerfer et al., 2017; Bao and Lu, 2020). In the construction industry, promoting circular strategies involves integrating technologies at each lifecycle stage to extend material lifespans and decrease dependence on virgin natural resources (Talla and McIlwaine, 2024). These strategies are fundamentally guided by the 3R principles of the circular economy.

The 3R principles, reduction, reuse, and recycling, are central to circular economy strategies (Pan and Hashemizadeh, 2023; Victar et al., 2023). Reduction focuses on minimizing inputs, such as energy and raw materials, as well as outputs, including waste, to improve environmental performance and reduce costs (Ghisellini et al., 2016). Reuse involves repurposing items or components for their original function (Victar et al., 2023), while recycling refers to transforming CDW into new products or structures, either for the same or different purposes (Mahpour, 2018). Although the 3R principles are applicable across the entire construction lifecycle, reduction is primarily applied in the construction and pre-construction phases, while reuse and recycling are emphasized during the post-construction phase (Atta et al., 2021).

2.2. Digital technologies

Digital technologies, closely associated with Industry 4.0 (the fourth industrial revolution), represent a transformative shift in the industry by utilizing data collection and analysis to create value-driven organizational systems and interconnected networks of products, people, and processes (Lieder and Rashid, 2016; Ranta et al., 2021). Key digital technologies—such as AI, big data, blockchain, the Internet of Things (IoT), and BIM—are crucial enablers of the circular economy (Kristoffersen et al., 2020). AI, encompassing deep learning and machine learning, has the potential to revolutionize CDW reduction and material reuse (Rodrigo et al., 2024; Wu et al., 2024b). Blockchain enables the traceability of material flow throughout the construction lifecycle, identifying CDW generation and opportunities for reduction (Rodrigo et al., 2024). BIM, renowned for optimizing project scheduling and improving material coordination, shows significant promise in minimizing CDW within the industry (Yu et al., 2022b).

Digital technologies can be categorized into three primary functions: (1) data collection, (2) data integration, and (3) data analysis (Liu et al.,

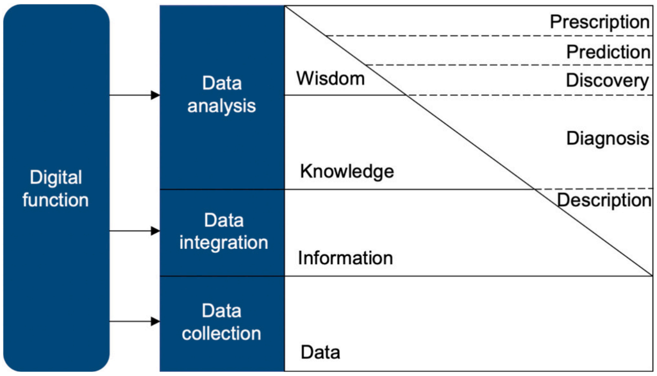

Fig. 1. Digital function categories (Adapted from Liu et al. (2022)).

2022). As shown in Fig. 1, these functions transform data into knowledge and, ultimately, wisdom. The process begins with data—raw symbols derived from observations of objects, events, or the environment. However, data alone lacks meaning and must be contextualized for practical use (Kristoffersen et al., 2020). Information emerges when data is interpreted within specific contexts, typically through descriptive analytics during the data integration phase (Liu et al., 2022). The data analysis phase then refines this information into actionable instructions, expertise, and valuable insights, representing knowledge. In contrast, wisdom refers to the predictive or prescriptive insights derived from this process (Liu et al., 2022; Rowley, 2007).

3. Methodology

This study employed a systematic literature review to explore how digital technologies have been leveraged to advance the circular economy within the construction industry. The process involved identifying relevant studies, followed by rigorous selection and analysis based on a well-defined research protocol (Cooper et al., 2018). As illustrated in Fig. 2, the methodology consisted of three steps: sample selection, descriptive analysis, and content analysis.

3.1. Sample selection

The paper conducted a preliminary search using Web of Science and Scopus as the sample sources. These databases were selected for their comprehensive coverage of scholarly works in the construction industry (Meho and Rogers, 2008; Bao et al., 2025) and their established effectiveness as search engines (Falagas et al., 2008). The initial search focused on the "title/abstract/keyword" fields, using a three-component search string. The identification of search keywords was theoretically grounded in the definitions of key concepts provided in Section 2. The first component included keywords "circular*" or "closed-loop" or "industrial symbiosis" or "industrial ecology" or "cradle to cradle" or "reverse logistics" to identify papers focused on the circular economy. The second component used keywords "digit*" or "big data" or "deep learning" or "machine learning" or "blockchain" or "internet of things" or "IoT" or "artificial intelligence" or "AI" or "BIM" or "building information model*" to filter for papers related to digital technologies. The third component incorporated keywords "building*" or "construction" or "built environment" or "civil engineering" or "structural engineering" to narrow the results to the construction industry. This search yielded 2737 papers from Scopus and 1386 papers from Web of Science (conducted on 10 January 2025).

Fig. 3 illustrates the sample selection process. Initially, four criteria were applied: document type (limited to reviews and articles), language (English only), source type (journals only), and the exclusion of duplicate entries. The first three criteria were applied using the database search engine, while the fourth was handled manually. The selection of articles and reviews was based on their reliability and influence (Opoku et al., 2021). After this preliminary exclusion process, 1495 papers were retained for further analysis.

To ensure the selection of papers specifically focused on the construction industry, circular economy, and digitalization, three rounds of manual review were conducted on the titles and abstracts of the 1495 papers. Specifically, if the main content of a review article focused on industries other than construction, it was excluded, even if the construction industry was also mentioned. The same criteria were applied to papers addressing circular economy and digitalization. Additionally, papers solely dedicated to conceptual models or theoretical frameworks were excluded. After these three rounds of review, 145 papers closely aligned with our research scope were identified, comprising 35 review papers and 110 research papers. To mitigate potential limitations of keyword-based searches, the reference lists of the review papers were examined, leading to the inclusion of 15 additional research papers. As a result, 125 research papers were selected for further analysis.

3.2. Descriptive analysis and content analysis

The study employed a two-step review process, consisting of descriptive analysis and content analysis. The descriptive analysis aimed to identify key themes across the 125 papers by examining publication trends and prevalent keywords. The content analysis involved a systematic coding process to extract relevant information addressing the following questions: (1) What are the main functions of digital technologies in fostering the circular economy? (2) How can these digital functions be leveraged to implement circular strategies?

Addressing the first research question requires identifying key digital functions that support the circular economy. Within the three overarching categories outlined in Section 2.2—data collection, data integration, and data analysis—specific functions that facilitate circular economy practices in construction were identified through content analysis. To answer the second research question, the identified digital functions were aligned with circular economy principles, guided by the 3R principles: reduction, reuse, and recycling, as discussed in Section 2.1.

4. Results

4.1. Descriptive analysis

Fig. 4 illustrates the yearly distribution of selected papers on the circular economy within the construction sector. In the first four years, only four papers were identified, while the subsequent four years saw a

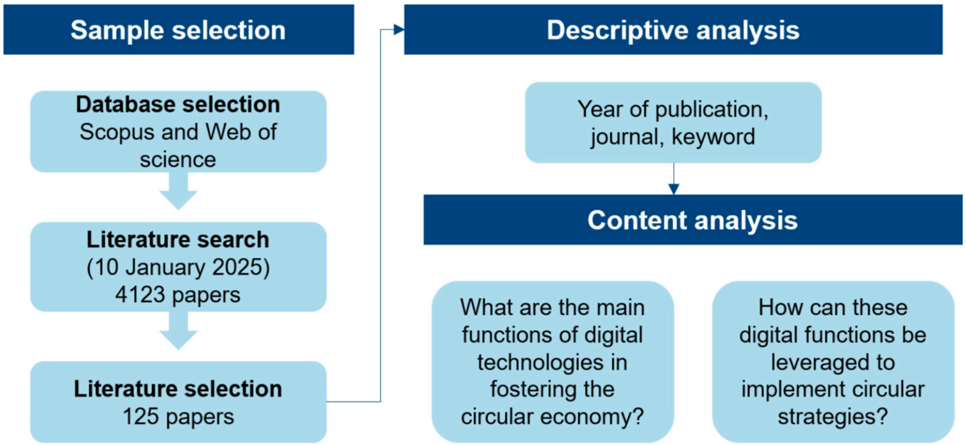

Fig. 2. Research methodology.

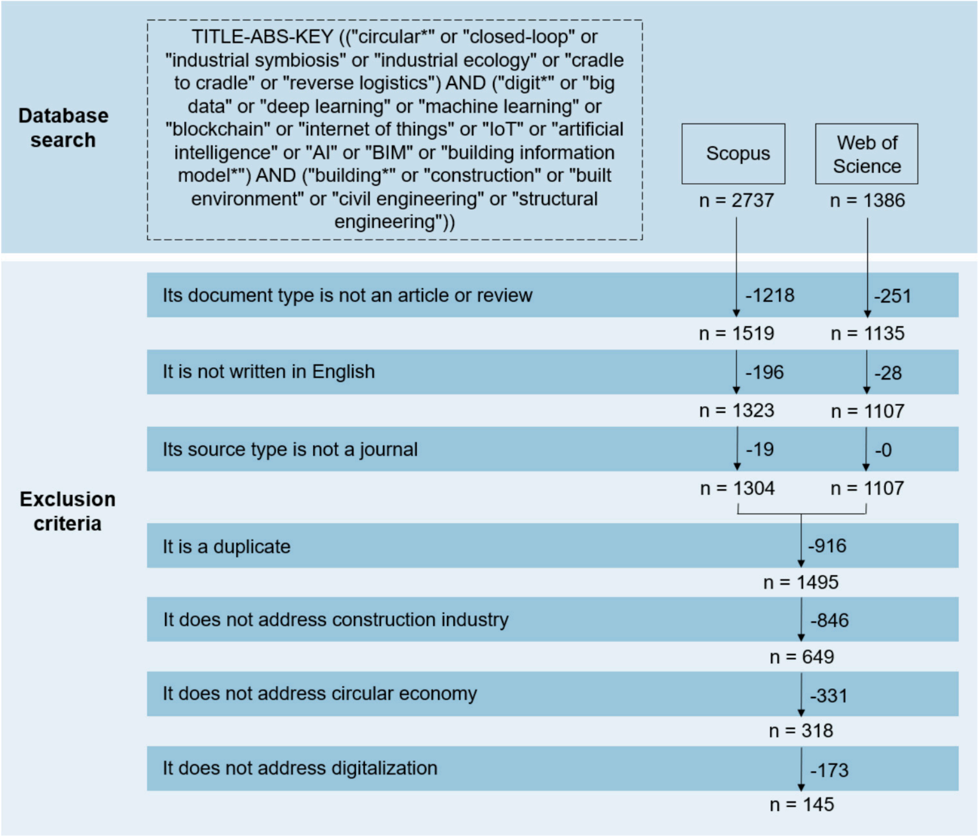

Fig. 3. The procedures of sample selection.

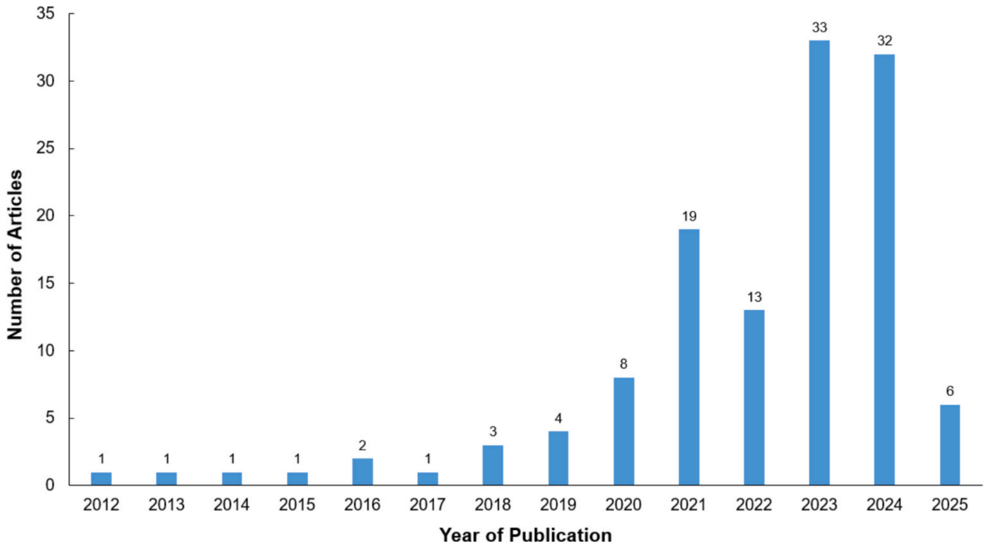

Fig. 4. Yearly publication.

notable increase to 10 papers, marking a 2.5-fold rise. Notably, over 80 % of the 125 papers were published in the past five years, highlighting the growing interest in this topic among various construction communities. This surge in publications reflects the increasing attention given to the circular economy in the construction sector, signaling a shift from linear to circular practices. Prominent journals such as Automation in Construction, Journal of Industrial Ecology, Journal of Building Engineering, Journal of Cleaner Production, Sustainability, Resources, Conservation and Recycling, and Waste Management have played a significant role in advancing knowledge in this field, as evidenced by their substantial publication output.

An analysis of the co-occurrence of author keywords was conducted to elucidate the interrelationships between topics. Synonymous keywords, such as “construction and demolition waste” and “CDW”, “building information modeling” and “BIM”, “geographic information system” and “GIS”, were merged. The co-occurrence network was then constructed based on keywords that appeared at least four times across the examined papers. The six most prevalent keywords were BIM, circular economy, CDW, machine learning, life cycle assessment, and industrial ecology. Fig. 5 reveals three distinct clusters. The first cluster

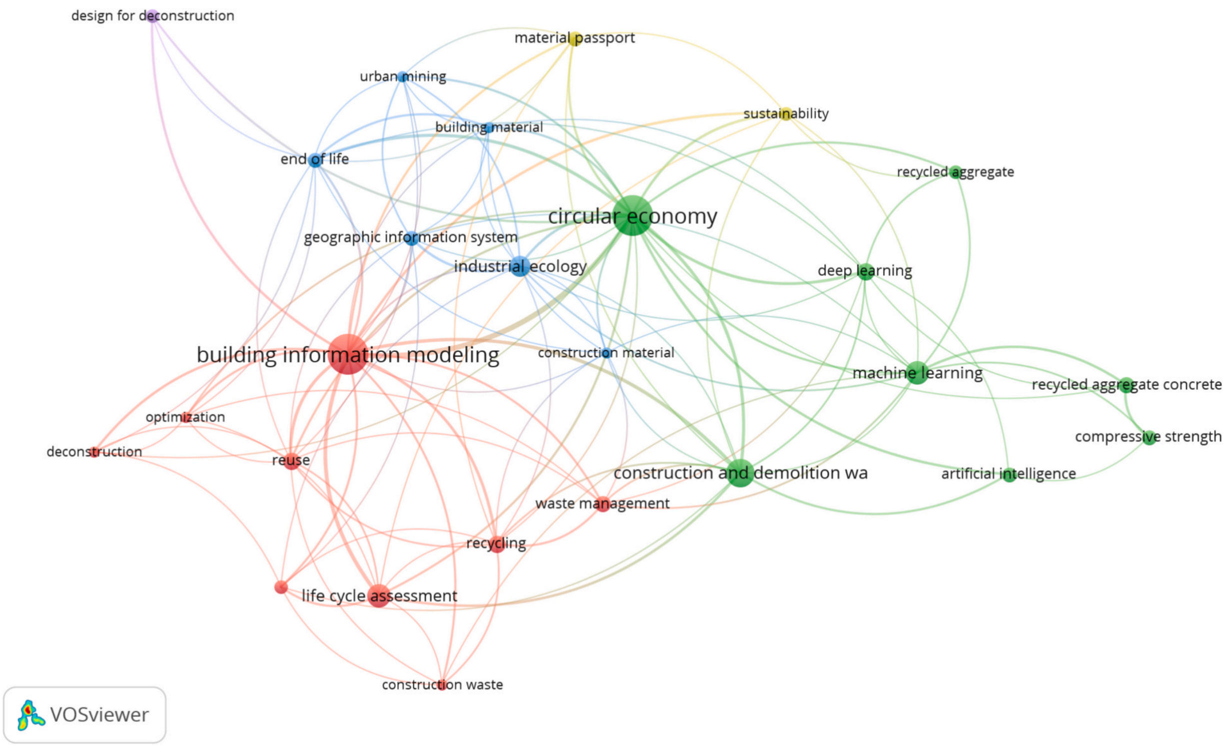

Fig. 5. The keywords co-occurrence network.

(red) underscores a robust link between BIM and circular principles, with a focus on reuse and recycling practices. The second cluster (green) highlights the integration of AI technologies, such as deep learning and machine learning, within the circular economy framework. The third cluster (blue) illustrates the theoretical overlap between circular economy concepts and industrial ecology.

4.2. *Main functions of digital technologies*

Table 1 presents 10 digital functions identified in the literature, illustrating how digital technologies can enhance circular construction performance. These functions were systematically categorized based on predefined criteria. Among the various functions discussed, the most frequently emphasized for enhancing circular economy practices include "assess", "auto-plan", "collect", and "estimate". Additionally, Table 1 outlines the four most prevalent digital technologies and their associated functions. From a technological perspective, mobile scanning is commonly used for building scanning to obtain modeling data for further analysis. Geographic Information System (GIS) is primarily employed for data collection, visualization, and tracking, leveraging its ability to provide geospatial data and offer a platform for spatial distribution displays. BIM, a key technology in the construction industry, plays a central role across several digital functions. AI is prominently applied in data analysis due to its advanced processing capabilities.

4.3. *Digital functions for circular strategies*

The study identified 15 strategies through which digital technologies can enhance the circular economy in construction. These strategies were then correlated with digital functions, with the circle sizes in Fig. 6 indicating the frequency of digital functions contributing to each strategy. Regarding the 3R principles, the literature emphasizes the dominant role of digital functions in facilitating recycling. Among specific circular strategies, design optimization, material stock estimation, and recycled aggregate property assessment are the most extensively studied. Further exploration of how digital functions can support the implementation of circular strategies is presented below.

4.3.1. *Circular strategies for reduce*

"Reduction" is the preferred principle, as it minimizes the use of natural materials and reduces CDW generation (Guerra et al., 2020). This principle is closely associated with the design and construction phases (Atta et al., 2021), where design optimization and construction planning have the most significant impact on material consumption and

Table 1
Identified digital functions and their supporting technologies.

Category	Digital function	Mobile scanning	GIS	AI	BIM	Others	Total
Data collection	Collect	13	3		2	5	23
Data integration	Visualize		4		2	3	9
	Trace		2		4	6	12
	Connect				2	4	6
Data analysis	Detect				1		1
	Assess			29	25	5	59
	Estimate			10	5	1	16
	Forecast			6	4	1	11
	Classify			11			11
	Auto-plan		1	2	16	4	23
Total		13	10	58	61	29	171

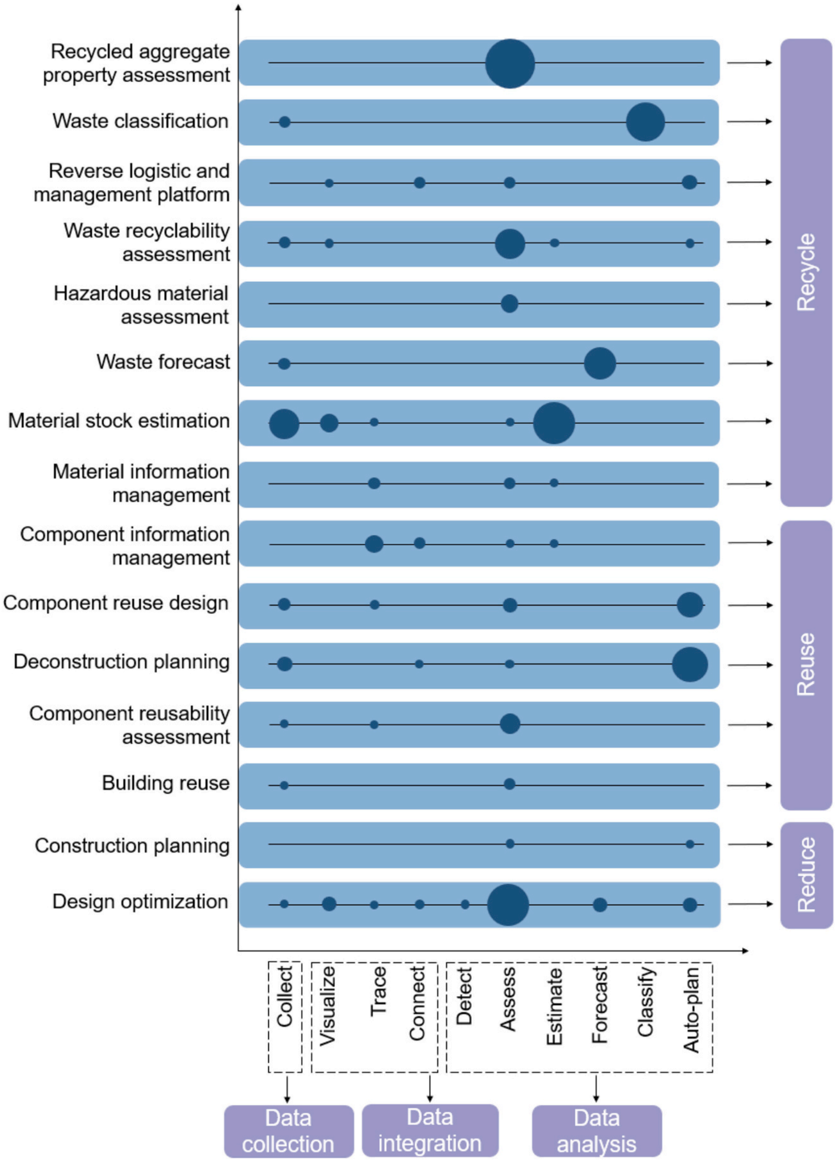

Fig. 6. The summary of digitalization-enabled circularity in the construction industry.

CDW production.

4.3.1.1. Design optimization. Design errors are commonly encountered in the construction industry, requiring corrections after construction has begun, and leading to rework and increased CDW (Won et al., 2016). BIM-based design error detection has proven effective in reducing CDW. Won et al. (2016) analyzed two South Korean projects and identified 136 and 381 design errors through BIM-enabled detection. Their results indicate that BIM could prevent 4.3–15.2 % of potential CDW. Additionally, trim loss in structural elements can contribute to CDW (Porwal and Hewage, 2012). Porwal and Hewage (2012) developed a model that uses one-dimensional cutting waste optimization techniques for reinforced concrete structures. This model integrates an optimization algorithm with structural BIM, enabling iterative adjustments to identify the most efficient cutting combinations for available rebar lengths.

Digital technologies provide forecasting capabilities that enable the quantification of CDW during the design phase, facilitating its reduction by allowing designers to compare and analyze CDW generation across different design options (Cornely et al., 2024; Sivashanmugam et al., 2024). For example, Quiñones et al. (2021) developed an automated method using a BIM-based multiplatform approach. By modeling building elements in BIM and assigning CDW quantities per unit of each element, precise CDW quantification was achieved. Furthermore, forecasting CDW can be enhanced by an adaptive neuro-fuzzy inference system, which combines fuzzy logic with artificial neural networks (ANN). Akinade and Oyedele (2019) conducted a study involving 117 building projects, utilizing historical CDW data from waste contractors for feature selection and model training.

Building design not only influences the type and quantity of CDW generated but also determines the potential for on-site CDW recycling (Fereydooni Eftekhari et al., 2024). The demand for quantitative methods and tools to assess building circularity is growing, supporting circular design principles (Morganti et al., 2024; Sahebzamani and Forcada, 2025). To enable robust circularity assessments, van der Zwaag et al. (2023) developed a decision support system characterized by high levels of automation and interactivity. Their assessment focused on three key factors: material utilization, environmental impact, and disassembly potential. Evaluating design for deconstruction (DfD) performance is widely recognized as a standard procedure during the design phase to assess a building's end-of-life impacts. DfD involves designing buildings and components to facilitate reuse or recycling during dismantling (de Lima et al., 2023). One design approach involves assigning QR codes to building components and linking them to images for easy identification, thereby aiding deconstruction and future reuse efforts (de Lima et al., 2023). Additionally, Akanbi et al. (2019) developed a framework to assess a building's deconstructability based on factors such as element type, quantity, connection type, and the specifications of prefabricated elements.

4.3.1.2. Construction planning. The use of "auto-plan" function can streamline on-site CDW reuse planning, thereby reducing the need for off-site treatment. For example, concrete waste generated during construction can be repurposed in subsequent activities that require clean fill material. Guerra et al. (2020) utilized a four-dimensional BIM approach to optimize concrete waste reuse planning at the project level. First, concrete waste quantities were estimated by subtracting the materials required for the structure from the purchased materials. Then, activities requiring clean fill material (i.e., concrete waste) in later construction phases were identified based on the construction schedule. By using a backward approach, concrete pours from earlier construction phases were analyzed to identify potential concrete waste that could be reused on-site in later phases (Guerra et al., 2020). Additionally, increasing the prefabrication rates of timber formwork in construction processes can significantly reduce waste and carbon emissions (Hao et al., 2024).

4.3.2. Circular strategies for reuse

The "reuse" principle is especially pertinent during the post-construction phase, emphasizing the repurposing of building components. This involves salvaging materials and components from deconstructed or renovated structures for integration into new projects, thereby extending their lifespan and reducing the demand for raw materials.

4.3.2.1. Building reuse. Building reuse includes renovation and regeneration efforts (Cinquepalmi et al., 2023; Mêda et al., 2023). Prioritizing renovation is essential to address aging, poor energy performance, and inadequate living conditions. However, challenges emerge due to insufficient as-built data, which can lead to unreliable design assumptions. To overcome these hurdles, Mêda et al. (2023) demonstrated a cost-effective scan-to-BIM method using LiDAR technology integrated into mobile devices. This approach allows for the efficient quantification of components and materials, improving the diagnostic process for existing buildings prior to renovation. Furthermore, promoting the conversion of nonresidential buildings requires a strategy focused on energy efficiency and a holistic approach to the circular economy. Cinquepalmi et al. (2023) tackled this challenge by developing a solution for the rapid, automatic pre-assessment of a building's potential for conversion into residential spaces.

4.3.2.2. Component reusability assessment. Compared to building reuse, component reuse is a more widely adopted strategy. A key factor in increasing component reuse rates is evaluating the suitability of structural components for reuse (Guerriero et al., 2024). Rakhshan et al. (2021b) developed an analytical framework using advanced supervised machine learning techniques to assess the economic feasibility of reusing load-bearing components. In addition, evaluating technical reusability is crucial. Rakhshan et al. (2021a) applied advanced machine learning to identify and rank key reusability factors based on stakeholder experiences. This resulted in a model capable of accurately and efficiently predicting the reuse potential of structural elements at a building's end-of-life phase. Moreover, regarding social reusability, findings from machine learning techniques emphasize the importance of regulatory authorities' perceptions as a primary social factor (Rakhshan et al., 2023).

4.3.2.3. Deconstruction planning. Deconstruction planning is crucial for optimizing the reuse potential of building components and materials (Sanchez et al., 2024). Effective implementation requires precise analytical models tailored to specific building archetypes (Mohammed et al., 2024; Sanchez et al., 2021). To overcome challenges such as incomplete modification records and deviations from original building structures, remote sensing presents a viable solution for acquiring accurate building data. Volk et al. (2018) introduced a cost-effective mobile sensor system for capturing interior room data, supporting building reconstruction, and inventorying elements and materials. This parameter acquisition serves as the foundation for developing accurate deconstruction models. Sanchez et al. (2021) proposed a method for parameterizing information models for deconstruction through a systematic analysis of BIM element spatial parameters. Given the wide range of possible solutions, selecting the optimal deconstruction planning approach requires evaluating the impact of various contributing factors (Akbarnezhad et al., 2014). Sanchez and Haas (2018) developed high-quality, feasible solutions for single-target deconstruction planning through rule-based recursive analyses aimed at minimizing ecological footprints and dismantling costs.

4.3.2.4. Component reuse design. Reusing building components is a vital strategy for promoting circular principles. However, designing with salvaged components presents challenges due to predefined dimensions and quality limitations (Tomczak et al., 2023). To address these challenges, Bertin et al. (2020) developed a toolset that facilitates the exchange of material properties between BIM software, structural calculation software, and a database of reusable elements. Data on used components can be efficiently gathered using 3D scanning and point cloud analysis (Olumo and Haas, 2024). By integrating finite element software, this approach enables the database to identify and incorporate reusable load-bearing elements into the model (Bertin et al., 2020). Additionally, Tomczak et al. (2023) proposed a flexible algorithm that substitutes new elements in designs with suitable reclaimed components by solving a matching problem.

4.3.2.5. Component information management. Effectively promoting circular economy principles through component reuse requires a comprehensive understanding of building components. Real-time provenance tracking and data retrieval of reusable components via a blockchain framework offer substantial potential for improving life-cycle management and advancing circular economy practices (Wilson et al., 2024). Jayasinghe and Waldmann (2020) developed a web-based method for storing comprehensive component information, including project details, component types, profiles, and attributes related to recyclability and reusability. Xing et al. (2020) created a bi-directional data exchange platform that connects physical building components with their BIM representations, enabling the tracking, monitoring, and management of life-cycle data, such as ownership records, maintenance logs, technical specifications, and physical conditions. Morganti et al. (2023) further enhanced data management with a cloud-based collaborative platform, allowing architects, project managers, quality control teams, and other stakeholders to access and manage relevant information.

4.3.3. Circular strategies for recycle

"Recycle" is the most frequently discussed principle in the literature, surpassing both "reduce" and "reuse". Similar to "reuse", "recycle" plays a significant role in the post-construction phase (Atta et al., 2021). In the construction industry, recycling involves converting discarded materials—such as concrete, asphalt, and glass—into new materials or components. This process not only conserves natural resources but also reduces energy consumption and mitigates greenhouse gas emissions associated with the production of virgin materials (Çetin et al., 2021).

4.3.3.1. Material information management. To support circularity and achieve high material recycling rates, comprehensive data on the materials of existing buildings is essential. The material passport serves as a key tool in this process, offering a detailed record of a building's material composition (Atta et al., 2021). The digitalization of material passports for circular construction is gaining momentum, as digital platforms act as efficient information brokers, fostering communication, collaboration, and data sharing (Atta et al., 2021). Integrating material passports with BIM provides several benefits, including error reduction, time and effort savings, and improved sustainability data sharing (Atta et al., 2021). Honic et al. (2019) introduced a BIM-based approach for the semi-automated creation of material passports.

4.3.3.2. Material stock estimation. Material stocks play a crucial role in the built environment, containing a wide range of accessible and recoverable materials (Arbabi et al., 2022). Modeling material stocks is essential for enabling stakeholders to access accurate data on secondary materials. A common approach for calculating material stocks involves determining material intensity by multiplying the building count in a given region by the average material content (Miatto et al., 2023). Sprecher et al. (2022) curated a database detailing the material intensity of buildings across the Netherlands. Utilizing an open database of material intensity parameters and semi-supervised machine learning, Vilaysouk et al. (2022) identified seven distinct building clusters within their dataset. Miatto et al. (2023) analyzed material intensities within specific building typologies, generating statistical summaries that highlight the variability in material intensities depending on building sizes and material composition.

In addition to material intensity, various methods exist for estimating material stocks. Kovacic and Honic (2021) introduced a combined data assessment and modeling approach, which enables the creation of a BIM model from point clouds and non-geometric data, forming the basis for BIM-based material stock estimation. Yuan et al. (2023) employed a machine learning regression approach to estimate building material stocks using easily accessible building features, incorporating six attributes: type, construction year, height, perimeter, total floor area, and floor count. Furthermore, Miatto et al. (2022) integrated material flow analysis with BIM to assess the quantity and usage scenarios of terracotta tiles and clay bricks in Italy.

Accurate city-level material stock data is crucial for predicting future CDW, developing sustainable management strategies, and facilitating city-wide CDW recycling (Honic et al., 2023; Huang et al., 2024). Kleemann et al. (2017) mapped the spatial distribution of materials across the city by integrating GIS data with material intensity values. Ajayebi et al. (2021) utilized a spatiotemporal stock-flow 3D model to estimate the stocks and flows of steel and concrete in urban buildings. To address the challenge of limited statistics and survey data, Bao et al. (2023) proposed a deep-learning model that integrates various remote sensing data sources to reliably estimate city material stocks. This model combines ground-level details from optical remote sensing with spatiotemporal data derived from nocturnal illumination.

4.3.3.3. Waste forecast. Pre-demolition audits are essential tools for maximizing material recycling during demolition processes (Akanbi et al., 2020; Cha et al., 2024; Maged et al., 2024). Soultanidis and Voudrias (2023) developed a modeling methodology to forecast CDW generation, estimating material quantities in 45 projects and categorizing them according to the European List of Waste using computer-aided design (CAD) software. Akanbi et al. (2020) introduced deep learning models to predict the quantity of salvageable CDW materials from buildings before demolition. For city-level CDW forecasts, Elshaboury and AlMetwaly (2023) proposed a machine learning approach that integrates economic indicators and CDW production data from 1965 to 2021, combining remote sensing with GIS to create a comprehensive spatial database.

4.3.3.4. Hazardous material assessment. Hazardous materials present considerable challenges to the recyclability of construction materials at the end-of-life stage. The lack of information on hazardous materials often results in unforeseen complications during reconstruction or renovation projects. Therefore, assessing the extent of pollution from existing building components is crucial. By leveraging data from hazardous waste inventories and building registers, machine learning techniques offer a promising approach to identifying hazardous materials in existing buildings (Wu et al., 2022). Wilhelm et al. (2024) achieved reliable and rapid predictions by training a machine-learning model on 1680 X-ray powder diffraction datasets.

4.3.3.5. Waste recyclability assessment. Reframing CDW as assets and assessing their recycling potential, alongside cost and environmental impacts, can foster a more circular approach to material use (Han et al., 2024; Honic et al., 2021). Recycling potential refers to the ability of materials to participate in a closed-loop flow, reflecting their material efficiency over their lifespan, for example, the proportion of a building's CDW that can be recycled (Sun et al., 2022). To enable comparisons of recycling potential across different building types, Sun et al. (2022) proposed a level-based scheme for assessing recycling potential. Mollaei et al. (2023) developed a decision-support tool grounded in an optimization framework, which estimates the prospective value of materials within buildings as they approach their end of life. Additionally, Saeed et al. (2023) employed multi-objective optimization techniques to determine the optimal quantity of material for each recovery scenario. Wang et al. (2024) developed a framework to assess the environmental impacts of various CDW management scenarios, quantifying both global warming potential and resource consumption across these scenarios.

4.3.3.6. Reverse logistic and management platform. Reverse logistics networks are increasingly employed to manage CDW recycling and facilitate its handling. These networks help identify optimal locations for CDW disposal facilities and determine suitable transportation methods for end-of-life CDW (Shi and Xu, 2021; Tsydenova et al., 2021). Tsydenova et al. (2021) introduced a multi-objective optimization model that provides insights into the quantity and location of sorting infrastructure, as well as tracking material flows across a wide regional recycling network. This model identifies the most appropriate recycling plants for integrating sorting screens to produce recycled aggregates for concrete manufacturing in construction (Tsydenova et al., 2021).

The demand for integrated information systems that can identify, coordinate, and evaluate circular economy collaborations across diverse projects is growing (Cocco and Ruggiero, 2021; Keena et al., 2025; Yu et al., 2023). Yu et al. (2023) developed a reference architecture for a web-based circularity information platform designed for the concrete supply chain. Effective communication and collaboration among stakeholders are critical in CDW reverse logistics operations. To support this, digital platforms are emerging to create ecosystems that facilitate stakeholder interaction. Barakat and Srour (2024) introduced an innovative digital platform aimed at enhancing stakeholder collaboration and optimizing CDW management strategies for contractors, adapting to market dynamics while aligning with government waste diversion goals.

4.3.3.7. Waste classification. The composition of CDW is complex, primarily consisting of solid or semi-solid waste with inherent recycling potential (Chen et al., 2023). Efficient recognition and categorization of CDW are essential for optimizing recycling processes (Wu et al., 2024a). In image recognition, traditional machine learning methods, such as support vector machines, have been applied for CDW image classification (Lin et al., 2022). However, these conventional approaches often struggle with differentiation and extracting high-level features. In contrast, deep learning algorithms provide greater robustness and accuracy compared to traditional image classification methods (Lin et al., 2023).

Convolutional neural network (CNN), a prominent deep learning technique, has been applied to the categorization of CDW. For instance, Hoong et al. (2020) utilized CNN to quickly and automatically identify the composition of recycled aggregates. Lin et al. (2023) achieved a more refined classification of CDW by integrating cyclical learning rates and transfer learning methods with deep learning models. Notably, computer vision stands out among various CDW composition sensing technologies for its cost-effectiveness, ease of maintenance, and versatility across different materials (Lu et al., 2022). Through model training, calibration, and empirical analysis, Lu et al. (2022) demonstrated the efficacy of a deep learning-enabled computer vision model in segmenting unstructured CDW within complex environments.

4.3.3.8. Recycled aggregate property assessment. Recycled aggregate is increasingly recognized as an eco-friendly and sustainable alternative in the construction sector. However, the properties of post-industrial and recycled materials often exhibit greater variability compared to natural materials (Dzięcioł and Sas, 2023; Ranjith et al., 2024). This variability highlights the need for simplified solutions to assess key parameters with minimal resources while mitigating risks. Tran et al. (2022) evaluated the compressive strength of recycled aggregate concrete using various machine learning models, including support vector regression, gradient boosting, and extreme gradient boosting, emphasizing the significant impact of cement content on compressive strength. Additionally, numerous mechanical properties of recycled aggregate concrete, such as splitting tensile strength, flexural strength, and axial stress, were extensively assessed (Al Martini et al., 2023; Dzięcioł and Sas, 2023; Ranjith et al., 2024; Raza et al., 2023; Shang et al., 2022; Ulucan et al., 2024; Zhang et al., 2025).

With the growing use of recycled asphalt shingles, reclaimed asphalt pavement, and other novel components in asphalt mixtures, concerns about the accuracy of conventional volume-based mixture design methods have intensified. To optimize pavement performance, Shang et al. (2022) developed a predictive model using a machine learning technique—specifically, random forest—to estimate the cracking resistance of asphalt mixtures. Among the various factors affecting recyclability and material quality in CDW, the size variability of aggregates plays a crucial role. Di Maria et al. (2016) employed image analysis techniques to accurately and efficiently estimate the size distribution of aggregates derived from CDW.

5. Discussion

The integration of digitalization is crucial for the successful implementation of circular practices in the construction sector, driving significant progress in this research domain. However, three key areas warrant further exploration, providing valuable insights to guide future research efforts.

5.1. Under-explored lifecycle stages

Fig. 6 illustrates the widespread application of digital technologies for design optimization, material stock estimation, and the assessment of recycled aggregate properties. This highlights the current emphasis on leveraging digital functions to support circular strategies across the design and end-of-life stages, enabling the reuse or recycling of components and materials. Given the long lifespan of buildings, life extension strategies—such as repair and maintenance—are prioritized at the EU level (Ingemarsdotter et al., 2021). However, these aspects are often overlooked in discussions about the circular built environment, particularly in relation to digitalization, which presents challenges for the broader adoption of digital technologies in circular processes (Çetin et al., 2022).

As noted by Munaro and Tavares (2021), the fragmented supply chain and limited understanding of circular tools hinder their widespread adoption in the industry. Therefore, fostering greater collaboration and knowledge-sharing among stakeholders is crucial to fully unlocking the potential of digital technologies in advancing circular practices throughout the built environment lifecycle. Researchers should focus on exploring and developing innovative solutions to support the implementation of circular strategies in construction, including creating training programs to improve digital literacy among industry professionals, establishing policies that incentivize the use of digital technologies, and promoting collaborative platforms to encourage knowledge exchange and cooperation.

5.2. Multidimensional scales of built environment

While the current focus on digital functions primarily centers on reuse and recycling, much of the ongoing research remains at the microscale, focusing on designing reusable components and assessing recycled aggregate properties. Circular practices in construction are generally categorized into three scales: micro (component/material), meso (project/building), and macro (region/city) (Pomponi and Moncaster, 2017). At the meso-scale, reuse and recycling practices in specific projects not only improve the efficiency of dismantling reusable components but also reduce storage costs, as these items already have a defined destination (Marzouk and Elmaraghy, 2021). At the macro-scale, extending reuse and recycling practices across regions offers an opportunity to leverage a larger market buffer for reused and recycled materials, addressing the challenge of managing material stocks within a single economy (Lu et al., 2023). Therefore, it is crucial to explore circular practices at the meso- and macro-scales to drive the transformation of the construction industry. Researchers should prioritize these broader-scale practices, focusing on inter-project and inter-regional collaboration potentials, as well as the integration of digital technologies to enhance component and material management, thus enabling more widespread reuse and recycling.

5.3. Sufficient data management mechanisms

Another critical challenge in the application of digital technologies is the lack of robust data management systems, particularly in the context of material passports. A major obstacle to the reuse and recycling of building materials is the absence of comprehensive data on materials at the end-of-life stage (Honic et al., 2019). Researchers have proposed the establishment and maintenance of material content data within a digital framework from the design phase, ensuring its availability throughout the building's lifecycle to maximize value recovery for the economy (Munaro et al., 2019). Although the concept of material passports has been tested in pilot projects, it has yet to be widely adopted in daily practices.

Çetin et al. (2022) highlight that the creation and maintenance of material passports requires substantial resources from social housing organizations, often surpassing their financial and human capacities for long-term sustainability. Future research should focus on developing more efficient, cost-effective methods for creating and updating material passports, as well as automating the data tracking and updating process. Additionally, involving third-party participants, such as architects or demolition companies, could help close the material loop by aligning material availability with demand during the design and demolition stages (Çetin et al., 2022).

6. Conclusion

This study critically examines the role of digitalization in facilitating the adoption of circular economy strategies in the construction industry through a systematic review. Through an innovative academic lens, it explores a refined and sophisticated mechanism by decomposing digital technologies into their corresponding digital functions. Through an analysis of 125 papers, 10 digital functions and 15 circular economy strategies were identified. Each function is typically supported by specific digital technologies; for instance, data collection is often enabled by mobile scanning, while AI is prominently utilized in data analysis tasks such as “assess”, “classify”, and “estimate”. Among the functions, those most frequently emphasized include “assess”, “auto-plan”, “collect”, and “estimate”. The reliance on digital functions varies across different circular economy strategies. For example, in recycled aggregate property assessment, AI is employed to “assess” the physical characteristics of recycled aggregates with diverse formulations. In contrast, material stock estimation focuses on how to “collect” data on existing buildings. Importantly, this study highlights three key research gaps for future exploration: (1) the application of digital technologies in under-explored lifecycle stages, with a particular focus on strategies for extending building life, (2) reuse and recycling practices at meso- and macro-scales, and (3) the development of robust data management mechanisms.

This study provides both theoretical and practical insights for stakeholders in the construction industry. Theoretically, it integrates concepts of digital technology and a circular economy, offering a comprehensive framework to understand their interrelationships. This includes exploring under-explored circular construction scenarios for applying emerging technologies such as BIM, AI, and mobile scanning. Practically, the study serves as a guide for industry practitioners, outlining best practices for leveraging digital technologies to enhance resource efficiency and sustainability. It also presents case studies illustrating successful applications and offers policy recommendations to facilitate the integration of these technologies.

While this review makes significant contributions to existing knowledge, it does have limitations. It primarily focuses on journal articles and reviews, potentially overlooking relevant research from conferences, books, and industry publications, which may present a partial view of the role of digital technologies in circular construction. Future studies should examine practical industry applications to bridge the gap between academia and practice. Additionally, this literature search was conducted using keywords, which may not fully capture the breadth of disciplinary topics. Some studies, particularly those focused on CDW management, may not explicitly include circular economy-related keywords. Therefore, future research should consider incorporating more inclusive keywords to provide a more comprehensive understanding of digital functions in advancing circular construction.

CRediT authorship contribution statement

Wuyan Long: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **S. Thomas Ng:** Funding acquisition, Supervision, Writing – review & editing. **Weisheng Lu:** Supervision, Writing – review & editing. **Luca Mora:** Validation, Writing – review & editing. **Zhikang Bao:** Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Writing – original draft, Supervision.

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.

Acknowledgements

This research is supported by Green Tech Fund (Project Number: GTF202110158) from the Environment and Ecology Bureau of Hong Kong SAR Government and Strategic Research Grant from City University of Hong Kong (Project Number: 7005899).

Data availability

Data will be made available on request.

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