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DIGITAL TECHNOLOGY ENABLED CIRCULARITY IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC STUDY

Shashini Jayakodi[1], Sepani Senaratne[2], Srinath Perera[3] and Keivan Bamdad[4]

ABSTRACT

The construction industry has a crucial role in a country's development process, nevertheless, it has a significant impact as it contributes to the emission of harmful gases, waste generation, and energy and resource consumption, making it one of the major contributors to environmental issues. By adopting Circular Economy (CE) principles, the construction industry can reduce costs, mitigate negative environmental impacts, address inherent complexities, and increase the resilience of urban areas to create more liveable, productive, and convenient cities. Utilising Digital Technologies (DT) is crucial in achieving circularity in construction. By identifying a knowledge gap in DT-enabled circularity, this research is aimed at exploring current research on DT-enabled circularity in the construction industry. A bibliometric analysis was conducted to address this aim and identify prominent authors, countries, and key research studies (co-occurrences of keywords). Around 66 documents published in Scopus were collected and analysed using "VOSviewer" software. The analysis revealed that a limited number of studies have been carried out in the selected research area. The results reported in the paper not only serve as a useful reference for both researchers and practitioners, but also signpost further works to be undertaken.

Keywords: *Bibliometric; Circular Economy; Construction Industry; Technology, VOSviewer.*

1. INTRODUCTION

The construction industry plays a crucial role in realising people's aspirations and needs through the physical execution of various construction projects (Razak Bin Ibrahim et al., 2010). However, the construction sector has a significant impact as it contributes to the emission of harmful gases, waste generation, and resource consumption, making it one of the major contributors to environmental issues (Esa et al., 2017). The environmental impact of the construction sector primarily stems from the consumption of non-renewable resources and the generation of pollutant residues, both of which are experiencing a rapid

[1] Postgraduate student, School of Engineering, Design and Built Environment, Western Sydney University, Paramatta, Australia, jayakodishashini@gmail.com
[2] Associate Professor, School of Engineering, Design and Built Environment, Western Sydney University, Paramatta, Australia, S.Senaratne@westernsydney.edu.au
[3] Professor, Centre for Smart Modern Construction, School of Engineering, Design and Built Environment, Western Sydney University, Paramatta, Australia, srinath.perera@westernsydney.edu.au
[4] Lecturer, Centre for Smart Modern Construction, School of Engineering, Design and Built Environment, Western Sydney University, Paramatta, Australia, k.bamdad@westernsydney.edu.au

increase (Núñez-Cacho et al., 2018). Construction activities have multiple impacts, including the generation of waste, consumption of resources, noise and air pollution, ecosystem degradation, and the emission of greenhouse gases due to vehicle and machinery operations (Oke et al., 2019). The World Business Council for Sustainable Development (2021) states that the construction industry is responsible for consuming approximately half of the world's virgin resources and generating close to 40% of global CO_2 emissions.

Traditionally, the construction industry has followed a Linear Economic (LE) model, which involves extracting virgin materials, processing them into new products that often cannot be disassembled, assembling them on-site, generating waste, and eventually discarding them before the end of their useful life (Cheshire 2017; Ellen MacArthur Foundation 2015). However, the limitations of the LE model have led to the emergence of the Circular Economy (CE) concept as a solution for balancing environmental protection and economic growth (Lieder & Rashid, 2016). The concept of CE has been discussed by various researchers and theorists. Boulding, identified as one of the first economists to present the CE paradigm, described it as an economic system that pursues long-term growth, zero waste creation, and sustainability (Pasqualotto, 2015). In 1988, O'Rorke has described the CE by formulating the term 'pre-cycling' which defines all actions that should be implemented at the initial stage of the product life to avoid waste generation rather than waste management (Pasqualotto, 2015). In 1989, Pearce and Turner introduced CE itself, although the concept has been date-back to the 1960s and it has been committed by several theorists, researchers, and vocational parties (Sariatli, 2017). Further, author has explained that in 2006, Anderson has presented a simplified model for CE which still appears as the idea of CE. CE is a regeneration system that minimises energy leakages, emission, and resource input, and waste by slowing, closing, and narrowing energy and material loops (Geissdoerfer et al., 2017).

The shift towards a CE paradigm in the construction industry would have great impacts in terms of reduction of pressure on non-renewable resources and of residues generated. Other claimed benefits would be the reduction of energy consumption or increase in the control on scarce materials dependency, creating more resilience to face environmental and economic crisis (HuertaCarrascosa et al., 2018 as cited in Gonz´alez et al., 2021). According to Charef et al. (2021), there are six categories of barriers in implementing CE in the construction industry as economic, sociological, political, organisational, technological, and environmental. Regarding technological barriers, most of them are related to the lack of appropriate tools and procedures. Emerging technologies play a vital role in achieving the desired level of the circular supply chain, which is fundamental to moving toward an integrated circular construction economy (Elghaish, et al., 2022). Industrial revolution has considered a most important part of the development of the world which emerged from the 18th century (Vinitha et al., 2020). The phenomenon of Industry 4.0 was first mentioned in 2011 in Germany as a proposal for the development of a new concept of German economic policy based on high-tech strategies (Mosconi, 2015). Industry 4.0 is based on the concept of a smart factory, where the machines are integrated with men through cyber-physical systems (Petrillo et al., 2018). Industry 4.0 encompass artifacts such as Artificial Intelligence (AI), robotics, big data, additive manufacturing, Internet of Things (IoT), synthetic biology, and physical cyber systems (Gavrila & Ancillo, 2021). The concept of Construction 4.0 focuses on the digitalisation of construction processes, enabling more effective coordination, design, and execution of infrastructure projects (Dallasega et al., 2018). According to Jemal et al. (2023), advanced technologies are crucial in leveraging new value from the CE and making strategies more cost-effective, as the scope of the Industry 4.0 concept continues to expand. Further authors have explained the integration of digitalisation within the Industry 4.0 framework can promote the broader implementation of the CE concept in the construction industry by enabling the interaction between products, processes, and individuals throughout the lifecycle via cyber-physical technologies. The emerging industrial revolution will enhance the symbiotic pursuit of new technologies and CE to transform extant production systems and business models for sustainability (Ramakrishna et al., 2020).

Although existing reviews studies on CE are contributing, they often have a narrow focus on linkages between CE and digitalisation. In particular, how different DTs can enhance diverse CE strategies in the construction sector is still not fully discovered. Research focusing on the practices of Industry 4.0 applications and CE is scant. More research is needed to explore the potential of integrating various Industry 4.0 technologies (i.e., IoT, blockchain, etc.) to foster CE adoption in construction. For example, (Gupta et al., 2021) identified the practices of Industry 4.0, cleaner production and CE, but this review was limited to manufacturing organisations in an emerging economy context. It is clear that, there is a research gap in the application of DT to achieve CE in construction industry. To contribute to enhanced understanding, a quantitative study using the bibliometric analysis technique was conducted on DT-enabled circularity in construction industry by reviewing the articles to identify the keywords and prominent authors, countries in the field. The following sections of this paper first describe the methods and process utilised in the study. The results in terms of the performance of publications and science maps are next presented and discussed. Further works to be undertaken to complement the results of this study are highlighted in the conclusion section.

2. METHODOLOGY

A systematic literature review is a rigorous and structured approach to identify, evaluate, and synthesise all available evidence on a specific research question, using a transparent and reproducible methodology (Peters et al., 2018). This type of review aims to minimise bias and provide a comprehensive overview of the current state of knowledge on a particular topic, and is commonly used in healthcare, social sciences, and other fields. A systematic literature review, using a bibliometric analysis, as conducted by Cobo et al. (2011), provides a comprehensive and quantitative analysis of the research output on a particular topic, highlighting the most influential authors, journals, and research trends in the field. This methodological approach allows for the identification of gaps in knowledge and research opportunities and can inform future research directions. Understanding the factors that influence the citation impact of articles is crucial for research evaluation (Sjögårde & Didegah, 2022). This study focuses on publications, and Scopus was chosen as the database to retrieve articles due to its extensive coverage of peer-reviewed journals and reliable academic information (Klapka & Slaby, 2018). The selection of search terms for the database search is an important consideration, as highlighted by Norouzi et al. (2021), as it greatly affects the study results. Therefore, the keywords used in this study were carefully chosen after reviewing an initial set of relevant research publications. The research process is depicted in Figure 1. To conduct the initial screening, a specific time period from January 2011 to January 2023 was chosen as the eligibility criteria. This selection was based on the emergence of the concept of Industry 4.0 in 2011.

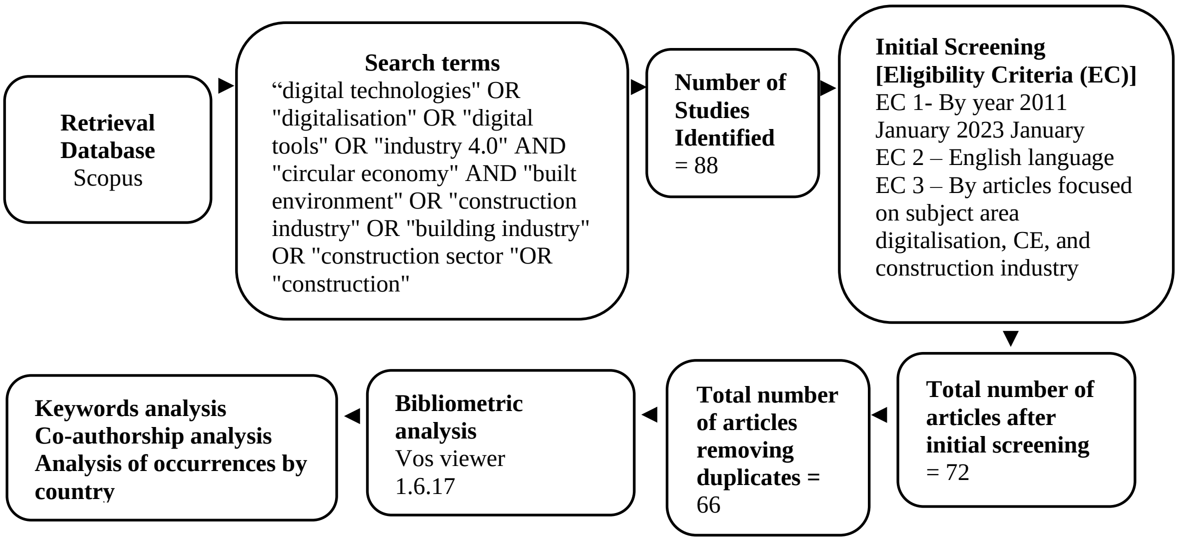

Figure 1: Research process

To conduct a comprehensive review, bibliometric analysis was employed to identify and examine relevant papers (Bellis, 2009). Bibliometric analysis is a computer-assisted methodology that enables the exploration of core research, authors, and their relationships by analysing publications related to a specific field or topic (Bellis, 2009). Co-authorship can be determined using bibliometric analysis, as noted by Castriotta et al. (2019). It was noted that extensive sources were accessed, including electronic databases, utilising keywords and the names of researchers who had published studies related to specifics or niche areas within the field of psychosocial studies (McCusker & Gunaydin, 2915). In this study, the literature was analysed using three bibliometric indicators: keyword co-occurrence, author co-authorship, and country affiliation. The collected data was then imported into bibliometric analysis and visualisation software for further examination. The software used for visualising and analysing trends in bibliometric maps was VOSviewer (van Eck & Waltman, 2010). VOSviewer allows the creation of publication maps, country maps, journal maps, and keyword maps based on networks and shared relationships (Hudha et al., 2020). The findings obtained from the bibliometric analysis and visualisations are discussed in the subsequent sections.

3. ANALYSIS AND DISCUSSION

3.1 KEYWORD ANALYSIS

Keywords are nouns or phrases that reflected the core content of a publication. The network of co-occurrence keywords illustrates the connections between research subjects and connection frames. In VOSviewer, the minimum number of occurrences of a keyword was set to 2, and out of 503 keywords, 60 met the threshold with 8 clusters, 1184 links, and total link strength of 1908. Figure 2 illustrates the clusters of keywords. The strength of the link connecting two keywords indicates the number of articles in which the keywords appear together, showing the connection of their corresponding research focuses. The main occurring keywords identified from the network are “circular economy, industry 4.0, construction sector, built environment, sustainable development, architecture design, Building Information Modelling (BIM), and digital technologies”. The generated network is presented in Figure 2.

It was identified that blockchain, modular construction, BIM, digital storage, Radio Frequency Identification (RFID), machine learning, automation, 3d printers, 3d modelling, Internet of Things (IoT), additive manufacturing, robotics, artificial intelligence, and digital twin are the visualised DT, which have links with the construction sector, Industry 4.0 and CE. Charaf and Emmit (2020) have identified seven new BIM uses in CE as digital model for sustainable end of life, material passport development, project database, data checking, circularity assessment, materials' recovery processes and materials' bank. Gordan et al. (2023) conducted a case study that explores the adaptation of Scan-to-BIM processes to develop digital models of demolition sites.

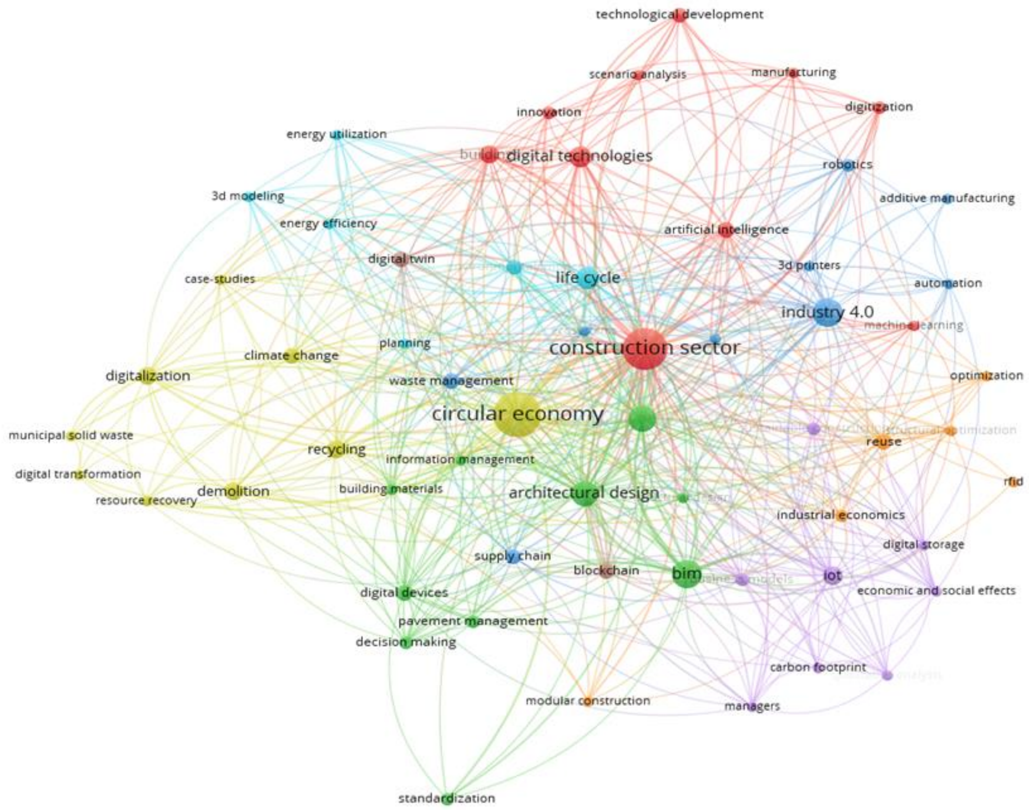

Figure 2: Co-occurrence of keywords (network visualisation)

The objective was to enhance the planning of deconstruction activities and maximise the utilisation of recovered materials. Similarly, Oreto et al. (2022) proposed a BIM-LCA (Life Cycle Assessment) study with the goal of integrating environmental considerations into road pavement design. The study aimed to promote the use of digital tools in the road industry and facilitate decision-making processes related to pavement maintenance, aligning with the principles of the CE. Table 1 depicts the application of disruptive technologies for a circular building industry in terms of different CE principles.

Table 1: Application of disruptive technologies for a circular building industry

	Design to disassembly, reuse, or recycling	Optimal material use	Re-covering by-products & waste
IOT	Insight into local conditions and sourcing options		
BIM	Calculating the percentage of circularity of a building during the design phase		Maintain material via registration of location and digitalisation: Material Passport
Robotics		Re-use of nonstandard materials (formerly discarded, non-industrially processed etc)	Enable re-use of materials due to dry assembly.
AI	Generative design methods that automate the use of nonstandard materials (former discarded, non-industrially processed etc)		
(Robotic) 3D printing		Zero waste production - Local resourcing - On-site construction and reduced logistics	Repeatedly recyclable building components
Blockchain	Enables transparency and secured privacy to make valid claims about sustainability		
Drone		Use of local materials	Enables the reuse of materials due to dry assembly.
AI		- remote construction in optimal workflow and high accuracy - efficiency & speed during construction phase	

Source: (Setaki & van Timmeren, 2022)

Ghaffar et al. (2020) suggested that mobile robotic sorting and reprocessing machines with innovative technologies such as AI and IoT could contribute to realising circular construction. The potential use of blockchain in waste trading processes for sharing, reporting, and auditing waste materials eliminating trusted intermediaries is to create wider circular business networks (Steenmans et al., 2021). Blockchain has the ability to create the platform to connect all construction project stakeholders to achieve circular buildings by closing the loop (Senaratne et al., 2021). The design and construction of circular modular construction projects promote sustainable material usage, maximise material recovery, and avoid unnecessary waste generation disposed to landfills (Wuni & Shen, 2020). According to the study of Copeland and Bilec (2020) which focused on provide solution to apply current technology to Building As Material Banks (BAMB) project, blockchain can be used to manage and create reliable transaction records between the supply and demand projects. Further to authors, the RFID data tag’s information can be stored within a blockchain to track the material’s location throughout its life cycle. Thus, it is clear that the identified digital tools have potentiality to implement CE in the construction sector. However, it is clear that still there is a gap in research on DT-enabled circularity in the construction industry, as the network map shows some limited enabling DTs than the potential DT tools.

3.2 CO-AUTHORSHIP ANALYSIS

The analysis of co-authorship networks has become a prevalent approach in understanding the intricate patterns of scientific collaborations, uncovering hidden or overlooked structural and dynamic aspects (Carchiolo et al., 2022). Various bibliometric methods are used to quantify the scientific collaboration among researchers and scientific communities (Ullah et al., 2022).

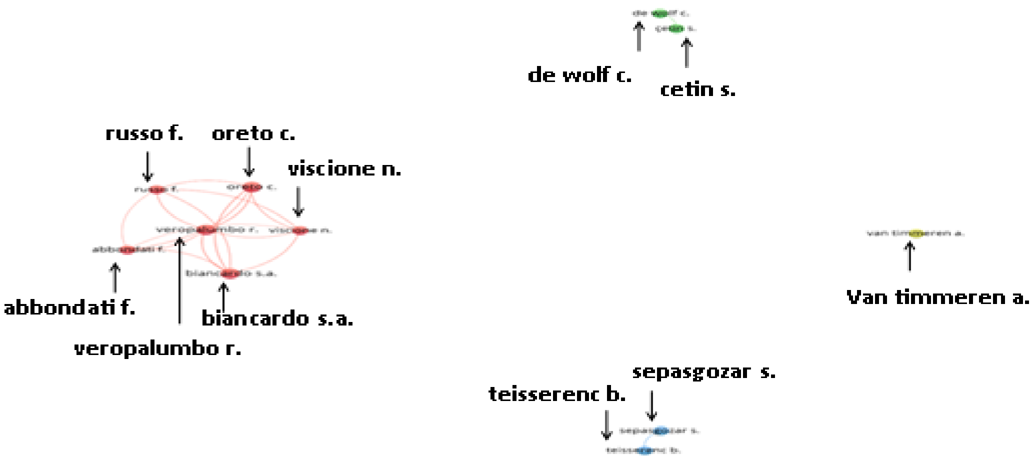

Figure 1: Co-authorship analysis (network visualisation based on links)

When conducting bibliometric analysis using VOSviewer, specific parameters must be set to align with the study's objectives. These parameters involve determining the thresholds for the minimum number of documents and citations for the subjects being analysed. In the case of authors, the minimum document threshold was set at '2', and the minimum citation threshold was set at '1'. Out of the 248 authors, only nine (3.6%) met these thresholds, as depicted in Figure 2.

Figure 2 illustrates the co-authorship network, where the size of a node indicates the number of connections an author has with other authors, and the colours of the nodes represent collaboration clusters. Among the four collaboration clusters, the only cluster with more than two authors consists of 'F. Russo', 'C. Oreto', 'R. Veropalumbo', 'N. Viscione', 'F. Abbondati', and 'S.A. Biancardo'. These authors form a strong network, accounting for eight out of 14 total connections (57%). The proximity and connectivity of researchers reflect their influence on each other. Given the dispersed nature of the clusters and the limited number of connections, fostering more collaboration among researchers is recommended for research on DT-enabled circularity in the construction industry.

Table 1, generated using the 'save as' function in VOSviewer, provides a summary of the analysis findings, ranking authors based on average citations. It reveals that although some authors have a relatively low number of connections, their publications have received frequent citations. This may be attributed to the novelty and comprehensiveness of their work. For instance, the highly cited paper titled "Circular Digital Built Environment: An Emerging Framework," co-authored by 'S. Cetin,' 'C. De Wolf,' and 'N.

De Bocken', presents a framework for implementing CE in the construction industry by identifying potential technologies. This framework serves as a promising starting point for further research at the intersection of CE and the construction sector.

Table 2: Co-authorship analysis of authors

Rank	Authors	Documents	Links	Total Link strength	Average citations	Average Publication year
1	abbondati f.	2	5	2	1	2022
2	biancardo s.a.	2	5	3	3.333	2022
3	de wolf c.	2	1	1	19	2022
4	oreto c.	2	5	3	3.3333	2022
5	russo f.	2	5	2	5	2021
6	sepasgozar s.	2	1	2	17	2021
7	teisserenc b.	2	1	2	17	2021
8	van timmeren a.	2	0	0	13.5	2020
9	veropalumbo r.	2	5	3	3.3333	2022
10	viscione n.	2	5	2	5	2021
11	çetin s.	2	1	1	21.5	2021

3.3 ANALYSIS OF PUBLICATIONS (BY COUNTRY)

The minimum threshold for the number of documents and citations required for a country was set at '2' and '1' respectively. Out of the 38 countries, only 19 (50%) met these criteria. Among these 19 countries, only 13 were found to be connected, as depicted in Figure 3 and Figure 4. In Figure 3, the size of the nodes corresponds to the number of publications, with larger nodes indicating a greater contribution from that country. Five distinct scientific clusters are identified and represented by different colours. Countries such as the Netherlands, Austria, the United Kingdom (UK), and Italy have shown a relatively higher number of publications (more than 5). Regarding co-authorship, the UK, Netherlands, Singapore, South Africa, and Spain exhibit some level of collaboration. Overall, the Netherlands and the UK emerge as the most active countries in terms of publication output and collaboration

Figure 2: Network Visualisation (by country)

4. CONCLUSIONS

In order to explore the current development of DT-enabled circularity in the construction industry, a bibliometric analysis was conducted. The analysis covered 66 articles published between 2011 and 2023. VOSviewer was utilised to perform a co-occurrence analysis to identify keywords, as well as a co-authorship analysis to identify authors and countries relevant to DT-enabled circularity in the construction industry. The findings revealed that modular construction, BIM, digital storage, RFID, machine learning, automation, 3D printers, 3D modeling, IoT, additive manufacturing, robotics, artificial intelligence, and digital twin are the prominent DT concepts within Industry 4.0 that are currently being adopted for implementing CE in the construction sector.

Among the authors, 'F. Russo', 'C. Oreto', 'R. Veropalumbo', 'N. Viscione', 'F. Abbondati', and 'S.A. Biancardo' were found to have the strongest network, but the author clusters showed significant distance and disconnection. Thus, it is recommended to foster more collaboration among researchers to enhance knowledge in this research domain. The most productive countries in terms of publications and collaboration related to DT-enabled circularity in the construction sector are the UK and the Netherlands, while China, Switzerland, and Italy are emerging countries that have published a significant number of papers in this field. It is further advised to share and synergise knowledge from various domains, with a focus on conferences and knowledge-sharing sessions to encourage researchers to exchange ideas and findings, thereby facilitating collaborative research.

Although the study successfully achieved its objectives, there are some limitations. The search terms used as keywords were carefully selected based on previous studies, but due to the emergence of industry 4.0 in 2011, publications in this area were limited. Despite these limitations, as the first bibliometric analysis in DT-enabled circularity in the construction industry, the study provides valuable patterns for future researchers to consider. It offers insight into key enabling dt that have the potential to implement ce in the construction industry, identifies active authors and leading countries in this field, and serves as a directory for literature search. The study's findings are also beneficial for industry practitioners seeking to understand the key DTs that can be implemented for ce in construction sectors across different countries. Future studies can focus on qualitative analysis of key potential DTs to implement CE in the construction industry, building upon the findings of this study.

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