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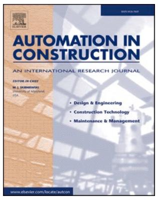

Review

Digital twin applications for overcoming construction supply chain challenges

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ABSTRACT

Despite Digital Twins' (DTs) growing popularity in the Architecture, Engineering, Construction and Operations sector, currently, only a limited number of studies have focused on the applicability and potential offered by DT to deal with the whole Construction Supply Chain (CSC) challenges, justifying the significance of the present study. As a response to provide a holistic insight into DT's contribution to overcoming CSC challenges, this paper follows an extensive literature review approach. This review aims explicitly to identify the existing applications of DT in dealing with current CSC challenges and explore its possible contributions by investigating examples of other industries that adopted DT to tackle similar challenges. Firstly, it utilises Scopus as a database to collect CSC-related data. Subsequently, it employs VOSviewer to extract and visualise CSC hotspots. Finally, this review conducts extensive discussions to identify the CSC challenges around the identified hotspots and the DT-provided solutions.

1. Introduction

With Supply Chain Management (SCM) initially introduced as a solution to tremendous competition among companies, the paramount importance of integrating cooperation tasks and operations into a unified supply chain, as opposed to managing them individually, has been recognised [1]. However, process fragmentation, monitoring deficiencies, insufficient process optimisation, and lack of real-time bi-directional information sharing between assets and stakeholders are among the significant challenges in leveraging the benefits of supply chain practices, with their threads being felt more palpably in CSC due to its fragmented nature and lower adoption of Information and Communications Technologies (ICT) and digital technologies compared to product-oriented industries [2]. These challenges impose CSC the risk of process interruption and insufficient collaboration among various project stakeholders [3,4], adversely yet widely affecting its overall performance and efficiency.

Digital Twin (DT) is an advanced digital technology that creates virtual replicas of assets and processes, establishing a bi-directional data flow between physical and digital twins [5–7]. The ability to create near-exact virtual replicas of products and processes with well-defined semantics has enabled DT to become a game-changer in many industries. However, notwithstanding exponential attention towards DT in many industries, it still lacks a broad and consensual definition due to its reliance on its application context. NASA first employed this technology on the Apollo 13 spacecraft to simulate various situations in space [6] After aerospace, manufacturing was the next industry in which DT adoption dramatically grew due to advancements in ICT, such as Big Data, IoT, Cloud Computing, and Communication, and AI technologies like Machine Learning and machine vision, which are crucial enabling technologies for DT.

Despite the challenges of implementing DT due to high initial investments [8] and substantial technical knowledge and expertise required [9], numerous studies have identified its advantages in industries such as product and process visualisation [10], simulation and optimisation of production-based systems [11], improved resilience and risk mitigation [12], improved collaboration and management [13] and enhanced decision-making [14]. However, maximum efficiency of DT is

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achieved when employed over the whole supply chain process rather than dedicating it to single phases, e.g., production or construction [15].

Over the past few years, the construction industry has realised the benefits of using digital technologies (DT) to deal with the complexities involved in buildings as sophisticated products. Although the manufacturing industry has been quicker in adopting DT, the construction industry has identified its potential to address critical issues and has been exploring its applications [16]. However, only limited studies focused on the holistic applications of DT in the construction industry [5,15], and this area requires serious attention. To narrow this gap, this study conducts a mixed literature review to identify the current challenges in construction and investigate how DT has addressed these challenges in the construction industry as applications and in other domains as potentials. The aim is to find model answers that can be applied in the construction industry.

The rest of this paper is structured as follows: Section 2 establishes the main research questions, providing a clear path to identify CSC's current challenges and how DT can help deal with them. Section 3 determines the methodological framework to answer these questions by describing the mixed method in this review, including various stages, from data collection to the analysing method and interpreting the data required for each research question. In Section 4, the mixed method is conducted, pinpointing current CSC hotspots and overarching themes as its ultimate goal. In Section 6, the overall goal of this research is achieved by finding CSC-specific challenges, and DT offered applications and potential to deal with them by dissecting the examples in the construction or other industries. Fig. 1 summarises the phases undertaken in this review study.

2. Research questions and literature search

The development of research questions in mixed methods studies is influenced by the study's goal, objectives, and purpose. The mode of framing for developing research questions in this study was sequential, as it is instrumental when conducting mixed-method research studies by allowing exploration and confirmation of research questions.

First, the main research questions were formulated based on logical explanations to conduct a comprehensive search with valid and accurate results. These questions, along with their corresponding explanations, include:

- RQ1) What are CSC literature's current, validated concerns/hotspots?

Identifying the current concerns/hotspots in CSC literature allows researchers to understand the landscape of the field and prioritise their research efforts accordingly [17]. Ensuring that concerns are validated not only upholds the credibility of the research but also assists in grasping the significance of qualitative research and the necessity of addressing validity issues [18].

- RQ2) What are the specific challenges around these CSC concerns/hotspots?

Understanding the specific challenges associated with CSC hotspots enables researchers to develop targeted solutions and strategies [19]. Examining these challenges can help identify barriers to CSC implementation, improvement areas, and innovation opportunities.

- RQ3) How has DT been applied to tackle the identified CSC challenges practically or theoretically?

Exploring the practical and theoretical applications of digital twin (DT) technology in tackling CSC challenges demonstrates its potential as a tool for driving advancements in the field [20]. Analysing existing use cases provides valuable insights into the effectiveness of leading technologies, including DT, and guides future implementations [21].

- RQ4) What are the possible DT potentials to deal with those identified CSC challenges over which this technology has not been applied sufficiently as a solution in the existing literature?

Identifying CSC challenges where DT has not been sufficiently applied reveals untapped opportunities for research and innovation [22]. By exploring the potential of DT in these areas, this review can contribute to the development of novel solutions and the advancement of the CSC domain [23].

3. Methodology

The formation and sequence of the research questions entail conducting a Mixed Methods Longitudinal Research (MMLR) based on contingent design, as the results of synthesising the findings gathered when responding to a given question initiate the subsequent question and the group of studies required to answer it. As demonstrated in Fig. 2, The MMLR in this review involves five phases: 1- Data collection (quantitative) 2- Scientometric analysis (quantitative) 3- Data interpretation and refinement (qualitative) 4- Investigating current CSC challenges (qualitative) 5- Investigating DT-provided solutions (qualitative).

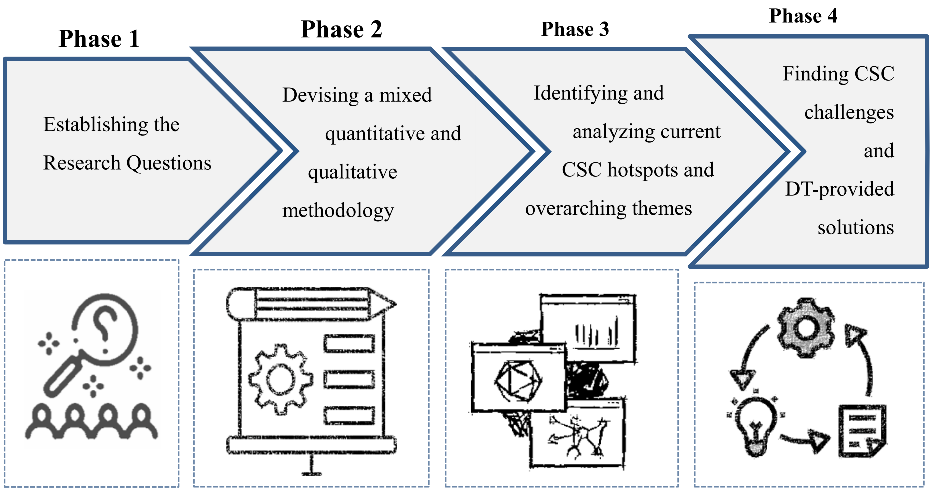

Fig. 1. Different phases carried out in this study.

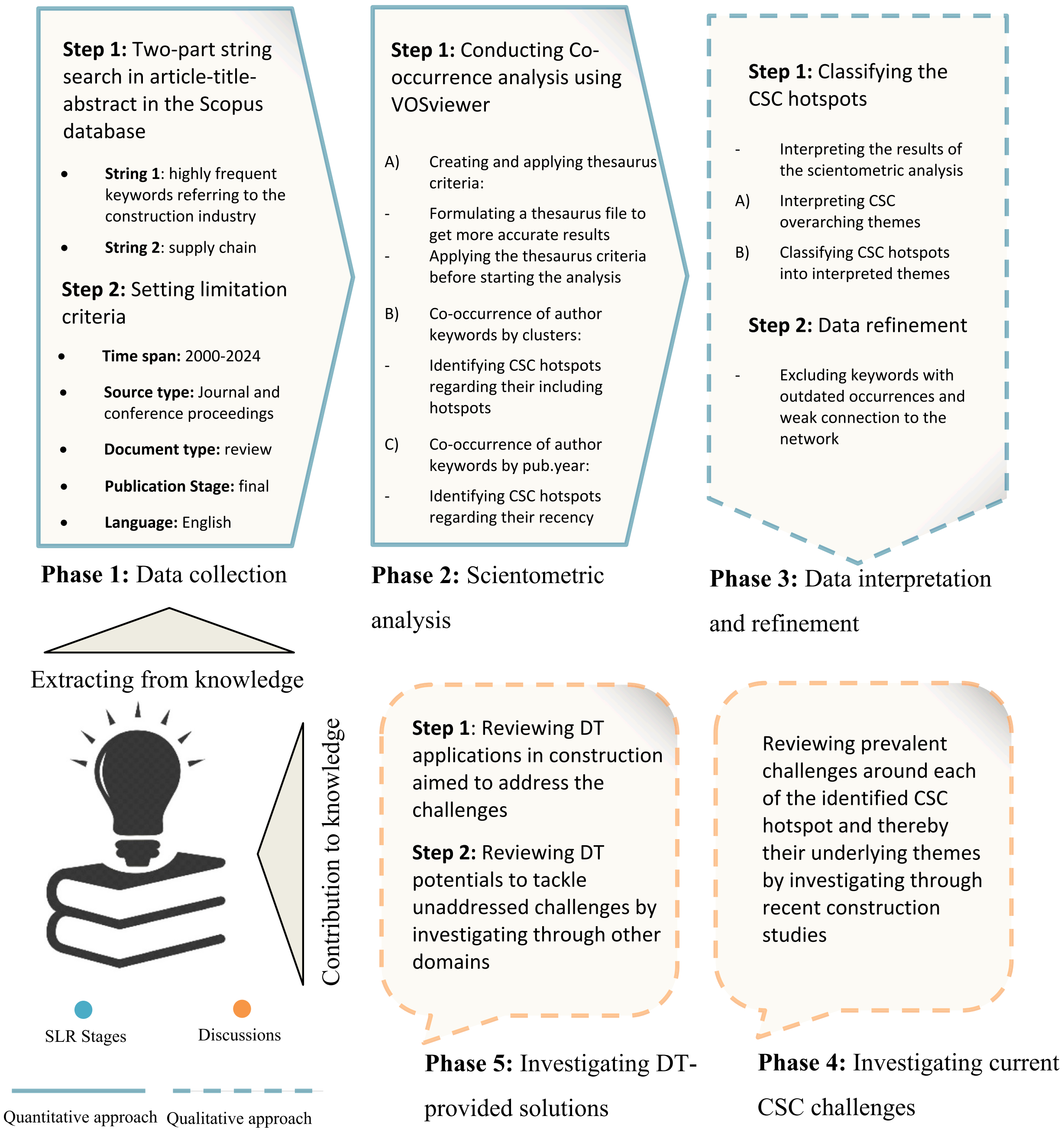

Fig. 2. MMLR framework.

A mixed-methods Systematic Literature Review (SLR) covers the first three phases, while CSC's current challenges and DT's current and potential contribution to these challenges are investigated through extensive discussions. More specifically, to address RQ1, a three-stage SLR strategy, including 1- Data collection using the Scopus database, 2- Scientometric Analysis and Visualisation of Similarities (VoS), and 3- Data interpretation and refinement, was adopted. Employing an SLR at the beginning of this extensive review process promotes the accuracy and comprehensiveness of input data required by subsequent qualitative analyses [24].

Phase 1 in the MMLR framework starts with the first stage of the mixed-methods SLR, where a keyword-based search is performed in the Scopus database. Phase 2 commences with the second SLR stage, where a Scientometric Analysis is carried out using the Visualisation of Similarities (VoS) method to map and visualise bibliometric networks. This method helps select and evaluate studies in a search field, such as the construction industry. The VoS technique is applied to extract valid CSC hotspots. Phase 3 is associated with the last SLR stage, during which the analysed data is refined to identify current CSC hotspots, which are classified into CSC overarching themes based on their backgrounds. This refinement process helps to identify validated and specific challenges around these hotspots in future attempts to answer RQ2.

Subsequently, this review implements phase 4 to address RQ2 by conducting in-depth discussions on the classified CSC hotspots based on their background themes. The goal is to identify specific challenges and deficiencies around each included hotspot and their corresponding themes.

Finally, the last phase in the methodological framework, initiated to address RQ3 and RQ4, pursues investigating DT-provided solutions. For RQ3, the present study conducted extensive discussions centred on the applications of DT in dealing with the extracted CSC challenges by dissecting the relevant and notable examples in the construction industry. Consequent to the RQ3 answers, the DT potential to combat those CSC challenges not addressed by this technology in the existing CSC literature is discovered to answer RQ4 by exploring other fields where DT has been successfully employed to tackle similar challenges.

4. Identifying CSC hotspots and overarching themes

From a holistic perspective, CSC involves six primary phases: Design, Manufacturing, Construction, Maintenance, Operation, and End of Life (deconstruction or demolition) [25]. Previous studies have found various critical hotspots, from sustainability and environmental criteria to advanced construction and manufacturing methods within CSC, along with their challenges, investigating each phase. The current section explains the SLR process undertaken in this review to identify relevant and up-to-date CSC hotspots.

4.1. Data collection using the Scopus database

For the first stage of the SLR, Scopus was selected for strict keyword searching in this study. The method for carrying out search tasks was based on two-part string searching in the article-title-abstract option. The comparatively larger number of published scientific works with more comprehensive coverage, plus Scopus's better performance than other databases, justified its adoption as the only database attended in this study.

Using appropriate keywords and Boolean connectors within every database is essential to search topics that are subjected to investigation effectively. The Scopus database, with its advanced analytical tools and expanded coverage, further underscores the significance of Boolean connectors in search strategies [26]. Using various synonyms for more general keywords is critical for conducting inclusive and accurate searches [27]. Thus, the authors combined various synonyms of “construction industry”, e.g., “AEC industry” and “construction sector” as a range of first keywords with “supply chain” as the second keyword using the two-part string searching method as an embedded feature of Scopus. This means the Boolean connector AND was distributed between these synonyms and “supply chain”. Moreover, since the authors did not encounter any controversial keywords in the literature, they did not use the Boolean NOT operator to exclude any keywords from their search in Scopus.

In this review, the time frame is limited to the research works published from 2000 to 2024, as it allows the capture of the most relevant and up-to-date information and research on CSC while increasing the chance to include emerging trends, technological developments, and recent best practices [28]. Such an inclusion helps analyse the current state of the field. Furthermore, to ensure higher credibility and reliability of the results, the source type is restricted to journals and conference proceedings due to their rigorous peer-review process. As shown in Fig. 3**.** With these criteria applied, the graph shows a noticeably upward trend—with research rising from 21 to 191 English and non-English publications.

However, a comparatively sheer surge can be seen from 2020 onward. This trend shows an unprecedented increase in CSC research interest in recent years, with a particular focus on sustainability, technology application, and long-term relationships [29], driven by the need to address unique challenges, such as the complexity of projects and the need for diverse supply chains. Another possible reason for this research growth is attempts to investigate factors influencing SCM and global research trends in SCM of construction projects [30], supply chain risk management in the construction industry, and the carbon footprint of the construction industry [31] with the ultimate goal of achieving sustainable and efficient SCM, and controlling global CSC impacts.

More inclusion and exclusion criteria are applied to this raw result to address the RQ1 more effectively by extracting more accurate results. The document type is set to “review,” and the publication stage is set to “final” as it allows the authors to increase the probability of identifying more validated and persistent hotspots in CSC. Also, the language was

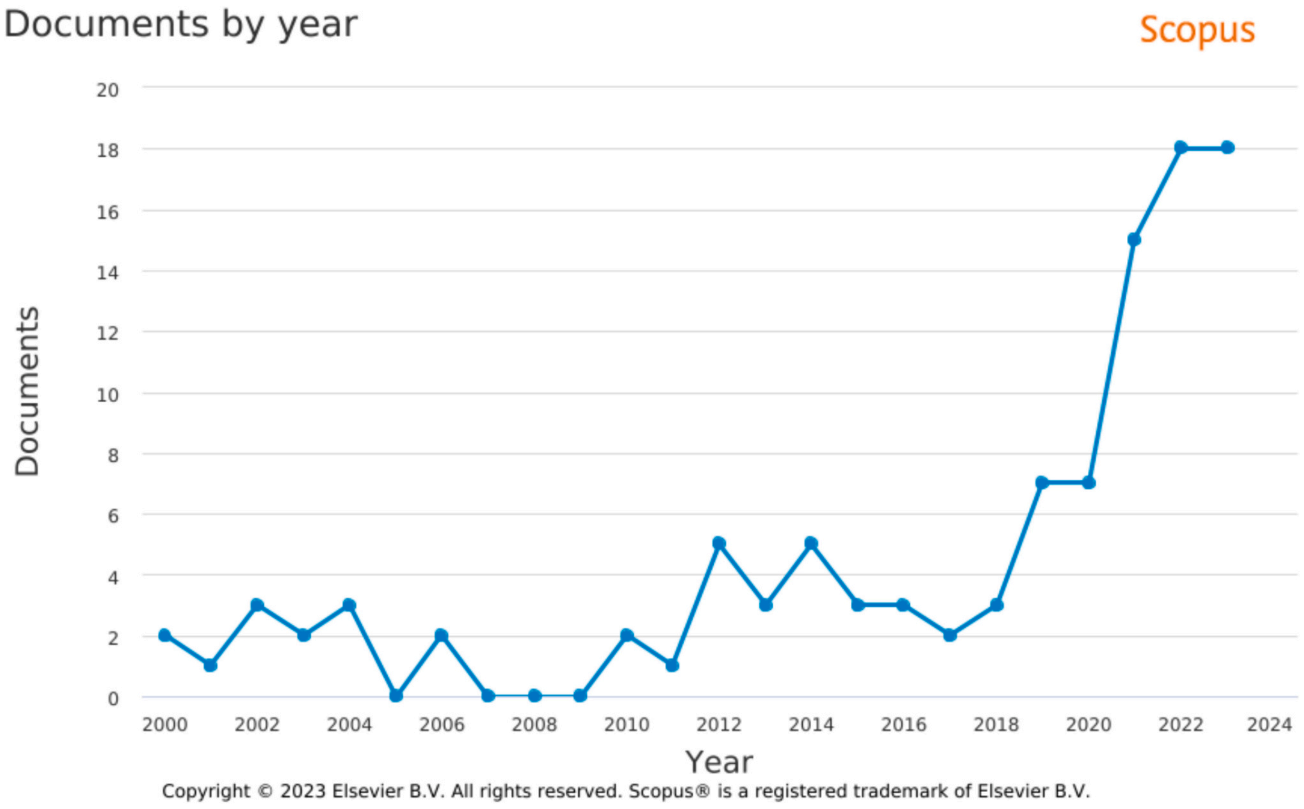

Fig. 3. Search results from 2000 to 2024- Before applying the inclusion criteria.

set to “English” for readability purposes. The following text is the complete script used in Scopus, applying all the mentioned criteria:

(TITLE-ABS-KEY (“construction industry” OR “building industry” OR “AEC industry” OR “AECO industry” OR “construction practices” OR “AEC practices” OR “AECO practices” OR “construction sector” OR “building sector” OR “AEC sector” OR “AECO sector”) AND TITLE-ABS-KEY (“supply chain”)) AND PUBYEAR > 1999 AND PUBYEAR < 2024 AND (LIMIT-TO (SRCTYPE, “j”) OR LIMIT-TO (SRCTYPE, “p”)) AND (LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (PUBSTAGE, “final”)).

After applying the inclusion criteria, 105 documents were obtained and subjected to further investigation. The results of using these additional criteria are demonstrated in Fig. 4.

Finally, after screening the titles and abstracts of the resulting papers, the number of documents that required in-depth analysis was reduced from 105 to 88.

4.2. Scientometric analysis and visualisation of similarities (VoS)

For the second stage of the SLR, two bibliometric methods were used in this section, including co-occurrence analysis and co-authorship. However, since one of the main objectives of this study was identifying the current hotspots in CSC (addressing RQ1) to find the significant challenges around these hotspots (addressing RQ2), the primary focus of the current bibliometric analysis is on the co-occurrence analysis. The co-authorship provides additional insight into active players in the CSC research field, encouraging scientific collaboration with researchers, institutions and countries in this field. For presenting the information in this bibliometric analysis, VOSviewer software version 1.6.19 was employed as it offers multiple Scientometric functionalities and is popular among various study fields for producing visualisations and maps showing network structures [32]. The size of each node in the networks visualised by VOSviewer corresponds to the number of appearances of that specific item in the publications subjected to analysis. In contrast, the distance between the nodes represents the strength of their relationship.

4.2.1. Co-occurrence analysis

Co-occurrence analysis helps identify keywords and themes associated with the main concepts of investigations in a field to examine its conceptual structure [33]. Conducting a keyword analysis of research papers can assist in rapidly identifying the research hotspots in the field of CSC [34]. In this study, the researchers conducted a keyword analysis of research papers from the Scopus database to quickly identify the research hotspots in the field of CSC, using “Author keywords” to ensure consistency in the representation of keywords [35]. To provide more reliable results, a thesaurus file was created during the data analysis process of this study that replaced similarities and synonyms with more familiar terms. For instance, “smart contract” was replaced by more familiar terms such as “smart contracts” to achieve accurate and precise results.

In this section, two types of results, including the co-occurrence of author keywords by clusters and the co-occurrence of author keywords by publication year, driven by VOSviewer co-occurrence analysis, were presented in two separate sub-sections.

4.2.1.1. Co-occurrence of author keywords by clusters. According to the keyword analysis, “construction industry,” “supply chain,” and “sustainability” were the three most dominant keywords, showing that a large body of literature considers sustainability to be a significant concern.

in the CSC field. Fig. 5 demonstrates the six clusters derived from the analysis along with their keywords. Each colour in the map represents a group of keywords clustered by the software. In this section, in addition to introducing the keywords in each software-driven cluster in order of their total link strength, the general theme behind each cluster is investigated. Details about the keywords, such as their definitions, are provided in Section 6 to avoid unnecessary repetitions.

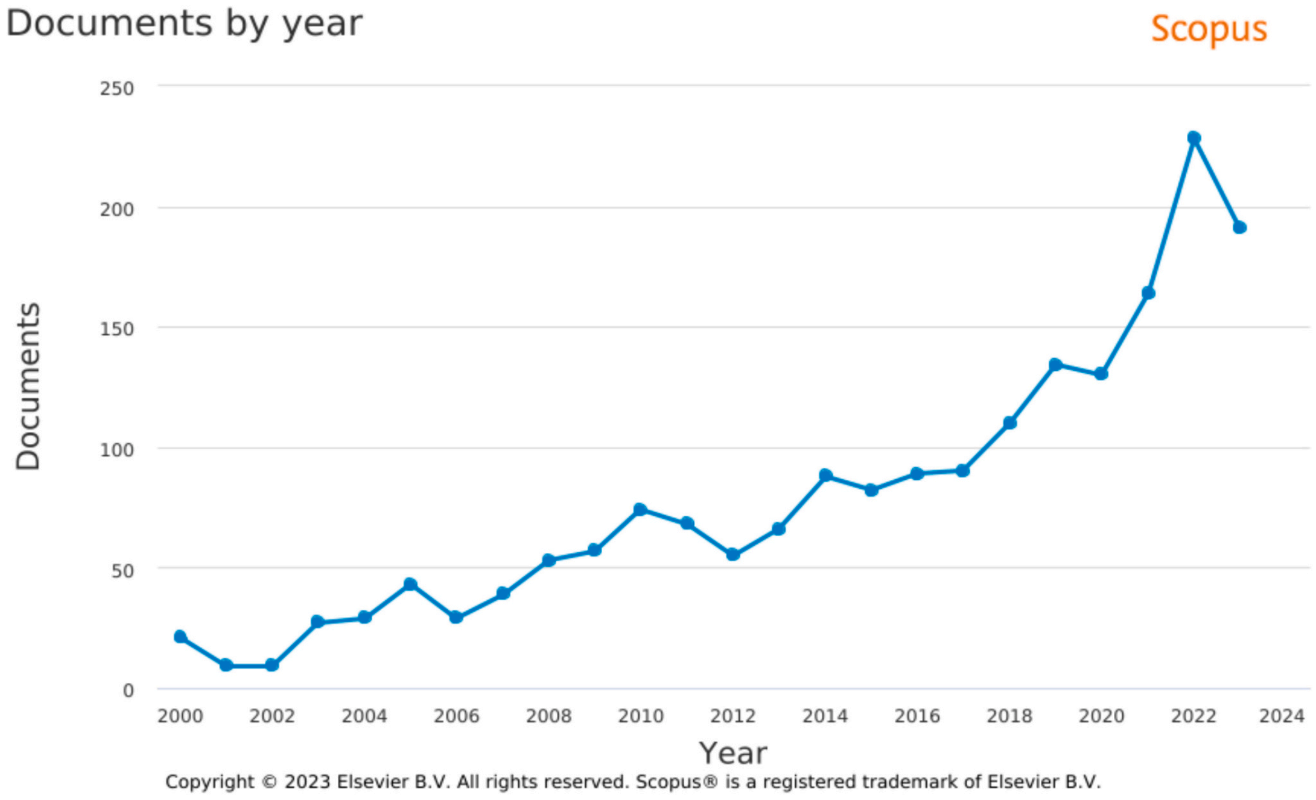

Fig. 4. Search results from 2000 to 2024- After applying the inclusion criteria.

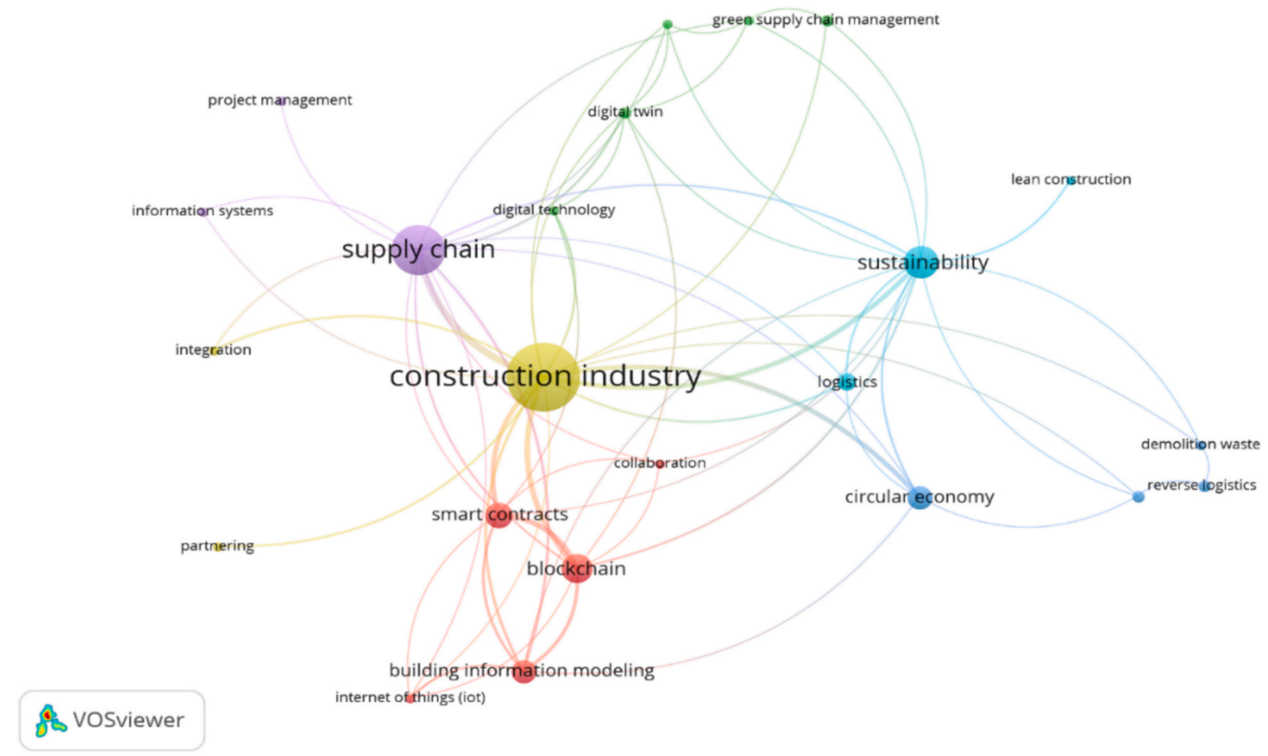

Fig. 5. VOSviewer results of the keyword cluster analysis.

- ***Cluster 1:*** This cluster contains six keywords in red on the map. The keywords are “blockchain”, “Building Information Modelling (BIM)”, “collaboration”, “Internet of Things (IoT)”, and “smart contracts”. Overall, this cluster represents a series of integrating advanced ICT technologies that can significantly improve information management among various parties involved in a CSC process.
- ***Cluster 2:*** This cluster, which appeared in green, includes five keywords: “carbon emissions,” “digital technology,” “digital twin,” “green supply chain management,” and “prefabrication.” The cluster

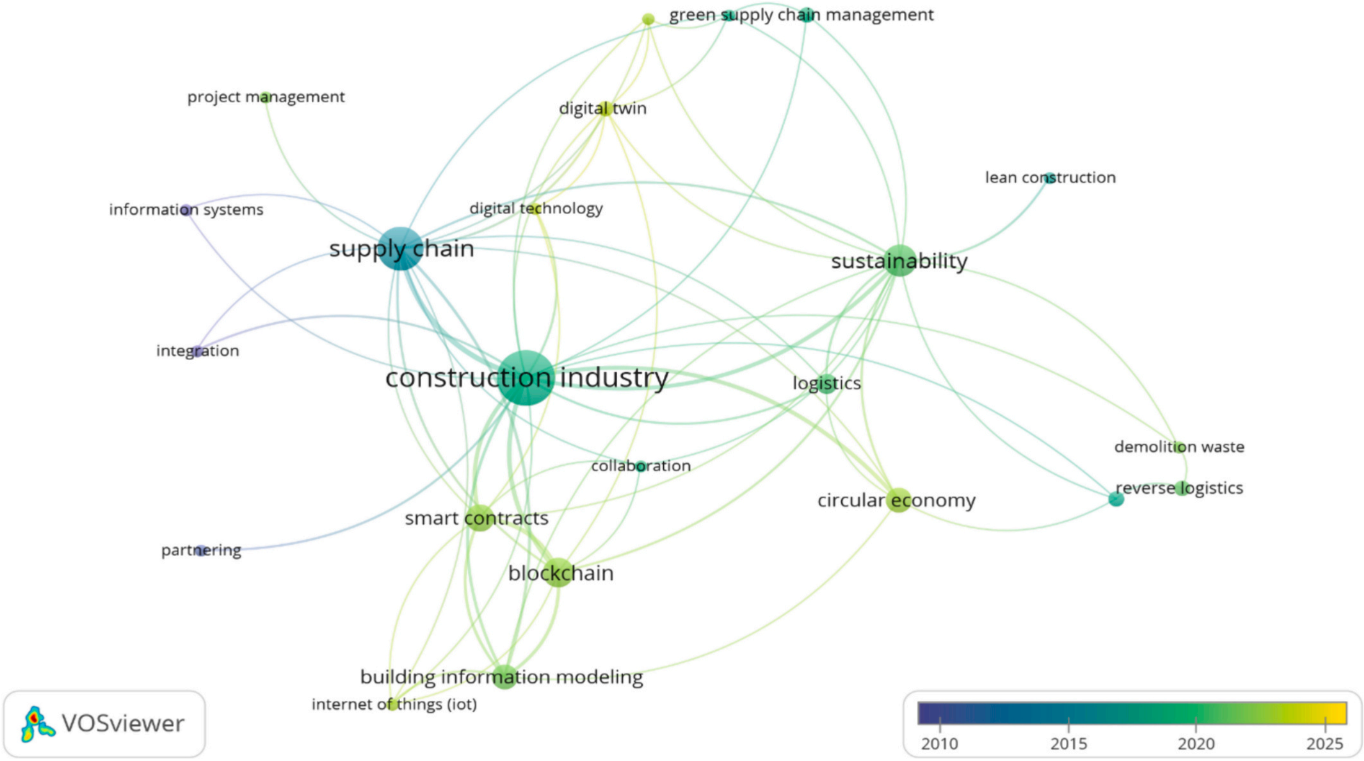

Fig. 6. VOSviewer publication year analysis.

is concerned with using digital and construction technologies to reduce carbon emissions and overall environmental impacts associated with CSC processes.

- ***Cluster 3:*** The third cluster includes four items and mainly concerns CSC-related environmental issues. It contains keywords such as “circular economy,” “demolition waste,” “reverse logistics,” and “waste management.”
- ***Cluster 4:*** The fourth cluster contains three items, which all target the integration aspect of CSC: “construction industry,” “integration,” and “partnering.”
- ***Cluster 5:*** This cluster encompasses three keywords, including “information systems,” “project management,” and “supply chain.” Its main idea revolves around information management in CSC.
- ***Cluster 6:*** The last cluster, with three keywords: “lean construction,” “logistics,” and “sustainability,” emphasises efficient transportation and use of construction resources and materials, which consequently leads to more sustainable CSC practices.

4.2.1.2. Co-occurrence of author keywords by publication year. To identify dated and recent concepts in literature, the overlay visualisation analysis of VOSviewer is employed, resulting in Fig. 6**.** This analysis uses a colour spectrum to represent the recency of each item, with blue nodes representing dated items and yellow nodes representing recent items. The size of each node represents the amount of author exploration within each keyword. This visualisation helps discover the current keywords being explored within the CSC realm.

Based on the results, the two main keywords of the construction industry and supply chain are well-established concepts with a fair history of exploration. The finding also reveals that the construction industry, supply chain, and sustainability are the core concepts according to the number of links with other keywords. While the attention towards technical implementation of cutting-edge ICT and digital technologies has exponentially risen over the past decades in the construction domain, the focus on more theoretical yet foundational concepts like integration in CSC has fallen, implying the urge for reconciliation between these two aspects. Additionally, concepts like integration and partnering seem to have gradually been replaced by collaboration and project management from 2020 onward. This is probably due to the heightened urge to meet sustainable criteria in the construction industry by intensely emphasising minimising time and energy spent during the CSC process and optimising the workflows in recent years. Other emerging hotspots include circular economy (CE), carbon emission, demolition waste (DW), logistics, and reverse logistics (RL), which are CSC's sustainability aspects.

In the area of efficient construction methods and techniques, data shows that, recently, prefabrication has received slightly more attention than lean construction within the CSC context, perhaps because it is more compatible with CSC processes, more reciprocal with sustainability purposes such as carbon emission control, and higher possibility for practically adopting emerging technologies such as digital twins.

However, to the authors' surprise, despite the increasingly popular sustainability trend within CSC studies, there seems to be a need for more research around the term Green Supply Chain Management (GSCM), implying a gap within CSC sustainability. Therefore, as a subsidiary task of the current review, GSCM challenges and possible solutions provided by DT will be focused upon within the corresponding theme.

4.2.1.3. Data interpretation and refinement. In the third stage of the SLR, this study sought to classify recent significant hotspots in CSC research into five distinct themes based on the results of the previous section. Table 1 demonstrates these groups: 1- CSC enabling ICT and digital technologies, 2- Sustainability and circular economy, 3- Logistics and transportation, 4- Efficient construction strategies and techniques, and 5- Construction supply chain management. Besides this classification, the average link strength and the average publication year for each theme were also considered in this figure. Comparing the themes according to these two items gives a general yet palpable idea about their significance and emergence.

Table 1
CSC overarching themes and specific hotspots.

Overarching themes	Hotspots	Avg. str. link	Avg. pub. year
1) Enabling ICT and digital technologies	Blockchain Smart contracts BIM Digital Twin IoT Digital technology Information systems	11.85	2020
2) Sustainability and circular economy	Sustainability Circular economy Carbon emission Waste management Demolition waste Green supply chain management	7.71	2020
3) Logistics and transportation	Logistics Reverse logistics	4	2020
4) Efficient construction strategies and techniques	Prefabrication Lean construction	3.5	2018
5) Construction supply chain management	Collaboration Project management Integration	2.5	2013

To seek a more updated and accurate perspective towards CSC's current hotspots, this study excluded partnering, which emphasises the role of collaborative studies in the CSC field to achieve more integration in real-world practices [36]. Further investigations revealed that it is a relatively outdated concept (with an average publication year of 2011), weak in its connection with other keywords (only one link with the network), and less frequent co-occurrence with only one linked term, construction industry, indicated by its distance from the connected term.

4.2.2. *Co-authorship analysis*

Many studies have highlighted the significant impact of co-authorships and collaboration networks on research productivity [37]. More extensive collaboration networks at the data creation stage positively correlated with research productivity and knowledge diffusion [38]. Moreover, diverse resources and specialisation have a significant role in these networks, reducing individual efforts and enhancing collaboration effectiveness [39].

4.2.2.1. Co-authorships between authors. To analyse the co-authorships between authors (Fig. 7), this review used the “co-authorship” setting in the VOSviewer, with “authors” as the unit of analysis and “fractional counting” as the counting method. The “minimum number of documents of an author” and the “minimum number of citations of an author” were set to 2. Out of 254 authors, 17 co-authorships were found. However, five were excluded because they were found to be individually authored, leaving only 12 co-authors who met the specified thresholds and were included in the resulting network. The VOSviewer network resulting from this analysis is shown in Fig. 7. Colour scaling indicates the most probable co-authorship period and the relevance of studies to CSC research. Moreover, the included co-authors are mentioned in Table 2, along with their analysed information.

Tennakoon et al. [40] contributed to CSC by investigating the low uptake of Reprocessed Construction Materials (RCMs) in Demolition Waste Reverse Logistics Supply Chains (DWRLSCs). Similarly, Tennakoon et al. [41] contributes to CSC by addressing the challenges faced in DW RLSCs, such as uncertainties, information deficiencies, and uncoordinated material flows. Moreover, Wijewickrama et al. [42] explore the role of information brokers in facilitating the transition from a linear

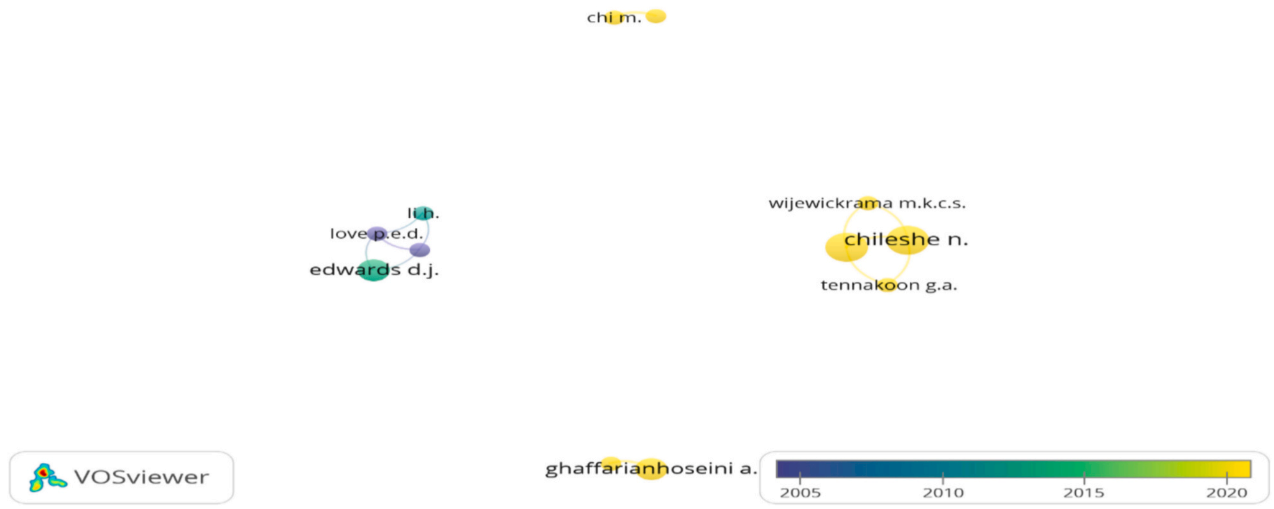

Fig. 7. VOSviewer co-authorship network of publications analysis.

Table 2

Co-authors, their number of citations, documents and total link strength.

Co-authors	Documents	Citations	Total link strength
Chileshe n.	4	75	4
Rameezdeen R.	4	75	4
Edwards D.J.	3	194	2
Ghaffarianhoseini A.	3	5	2
Chi M.	2	45	2
Dhawan K.	2	5	2
Irani z.	2	275	2
Love P.E.D.	2	275	2
Tennakoon G.A.	2	23	2
Wijewickrama M.K.C.S.	2	52	2
Xu Y.	2	45	2
Li H.	2	118	1

to a CE model. Furthermore, Wijewickrama et al. [43] examined the role of Quality Assurance (QA) in the Reverse Logistics Supply Chain (RLSC) for DW and proposed a conceptual framework for enforcing QA in the RLSC of DW.

Dhawan et al. [44] addressed the industry fragmentation issue and explored opportunities for greening construction transport by highlighting the importance of logistics in CSC and proposing a research framework for optimising and decarbonising construction transport. Likewise, Dhawan et al. [45] examined the sustainability impacts of implementing a combination of Enterprise Alliance delivery strategy and Construction Consolidation Centre (CCC) logistics solution in New Zealand's public water infrastructure procurement contracts by emphasising the unique spatial, market, regulatory, and economic circumstances of New Zealand and establishing a research framework to investigate the outcomes of this combinatory approach.

Xu et al. [46] integrated blockchain into CSC processes thus making significant contributions, including 1- Identifying key application areas 2- Assessing current research status 3- Highlighting challenges and future research opportunities 4- Synthesising knowledge on blockchain applications.

Love et al. [47] conducted a landmark review study that adopted a holistic approach to CSC. They presented a seamless project SCM model that aims to bridge the design and production processes in construction projects. The proposed model was validated by industry practitioners, providing insights into its practical relevance and applicability. Their feedback is considered and reflected upon, further enhancing the model's potential impact on CSC. They identified several areas for future research, such as exploring the legal aspects of implementing the model, developing a benchmarking framework, investigating the use of quality function deployment, and addressing probity issues in selecting project team members. These research directions can guide further studies and contribute to advancing the understanding of SCM in the construction industry.

Similarly, Love et al. [48] focused on the fragmentation issue in CSC practices and emphasised the importance of long-term alliances among construction organisations, customers, and suppliers for improved performance and innovation. They argued that short-term alliances often inhibit feedback and learning, which are essential for developing trust and cooperation among project partners. They proposed a model founded on Total Quality Management (TQM) principles to support education and improve inter-organisational relations in CSC.

4.2.2.2. Network of institutions. To investigate the network of institutions, this paper analysed the institution's co-authorship using “organisations” as the unit of analysis and “fractional counting” as the counting method. To ensure more accurate results, a thesaurus file was created that eliminated duplicates. The “minimum number of documents of an organisation” was set to 2, and the “minimum number of citations of an organisation” to 2. Out of the 155 organisations affiliated with co-authors in the identified studies, this paper identified 14 institutions meeting the criteria illustrated in Fig. 8**.** Also, detailed information about these institutions is provided in Table 3.

In Table 3, readers find an overview of the distribution of CSC citations across different institutions. The Department of Building and Real Estate at Hong Kong Polytechnic University stands out as the leading contributor with 563 citations. The Department of Civil Engineering at the University of Hong Kong is closely followed, with 477 citations. Other significant contributors include the Department of Civil Engineering at Loughborough University and the Department of Information Systems and Computing at Brunei University in the United Kingdom, which secured 440 and 275 citations, respectively. Although there is a need for more efficient collaboration among institutions on CSC-related research, this data demonstrates the diverse participation of institutions in this area and emphasises the Department of Building and Real Estate at Hong Kong Polytechnic University as a major contributor to this academic field.

The absence of links between institutions on the map (Fig. 8) indicates that from 2000 to 2024, the review studies on CSC did not involve collaboration or co-authorship between different institutions, and they were primarily conducted independently within individual institutions. However, research in various fields, such as.

information systems [49], has shown that the absence of co-authorship links between institutions does not necessarily indicate

Fig. 8. VOSviewer analysis of co-authorships between research institutions.

isolation. Other forms of collaboration, such as citations, shared funding sources, or informal networks, can still exist and contribute to the field's development. Overall, these findings highlight a real need for collaboration through co-authorship among research institutions to exchange knowledge in the CSC field via review papers.

However, Fig. 9 suggests that the most influential institutions in terms of citations are not necessarily the ones that made the recent contribution to the field. For instance, the Faculty of Science and Engineering at the University of Wolverhampton in the United Kingdom and the School of Future Environments at Auckland University of Technology in New Zealand are the most active institutions in terms of research recency, with an average publication year of above 2022 for each. In the third and fourth places are the School of Civil and Hydraulic Engineering situated at Huazhong University of Science and Technology in China and the Bartlett School of Construction and Project Management at University College London (UCL) in the United Kingdom, with average publication years of 2022 and 2021, respectively.

4.2.2.3. Network of countries/regions. To investigate the network of countries/regions, the authors analysed co-authorship using “countries” as the unit of analysis and “fractional counting” as the counting method. The “minimum number of documents of a country” and the “minimum number of citations of a country” were set to 2. Out of the 35 countries identified in studies, 15 met the thresholds. These countries, along with their connections, are illustrated in Fig. 9. Fig. 9 displays the average publication year for each country using colour grading, with the colour nodes corresponding to the years in the legend. Besides, Table 4 provides detailed information about these countries.

According to Table 4, countries with significant contributions in terms of citations are the United Kingdom, with 1732 citations, Hong Kong, with 873, Australia, with 668, and China, with 628, while the ones with the fewest citations include **Nigeria**, with 4, New Zealand, with 5, Malaysia, with 15, and **the United Arab Emirates**, with 29.

The ticker links in Fig. 9 demonstrated the interconnectedness between countries, as depicted by the United Kingdom—Australia, Hong Kong—China, and Australia—China. Also, the nodes' sizes represent countries' relevance to the CSC study area, with the United Kingdom, Australia, Hong Kong, and China being the most relevant to the study. On the other hand, countries with nodes having smaller sizes and lower connections, including Portugal and Denmark with one connection with the United Kingdom, the United Arab Emirates with two connections with Nigeria and the United Kingdom, Nigeria with two connections with the United Arab Emirates and Hong Kong, Brazil, and New Zealand with two connections with the United Kingdom and Australia, showed less significant contributions to knowledge generation and exchange in this research area. Finally, Malaysia and India showed zero connections with other countries in the network, showcasing CSC studies as having immense potential for growth in these countries.

Regarding recency, it can be extrapolated from Fig. 9 that there was a rise in publications from purple colour-coded countries like the United Kingdom in 2014, Singapore in 2016, Hong Kong, the United Arab Emirates, and Nigeria in 2017. Moreover, the same trend likely occurred for Denmark and Australia in 2018 and for Canada and the United States in 2019. The following three countries, including China, with an average publication year of 2020, Portugal, and Brazil, with 2021, are active in the CSC research field. Finally, with an average publication year of 2022, New Zealand is the most active country in this field, according to research recency.

5. CSC current challenges and DT possible solutions

Responding to RQ2 and RQ3, this stage fulfils two main goals: 1-spotting current challenges in each identified CSC hotspot and 2-reviewing the contribution of DT to dealing with each spotted challenge. The first objective is approached by conducting investigations on construction literature through discussion. In contrast, the second objective is reached by elaborating on existing theoretical and practical research studies as examples in construction and other industries.

Table 3
Research institutions, their rankings, number of citations and documents.

Research institutions	Documents	Citations	Ranking
Department of Building and Real Estate, Hong Kong Polytechnic University, Kowloon, Hong Kong	6	563	1
Department of Civil Engineering, University of Hong Kong, Pokfulam, Hong Kong	2	477	2
Department of Civil Engineering, Loughborough University, Loughborough, United Kingdom	3	440	3
Department of Information Systems and Computing, Brunei University, Uxbridge, United Kingdom	2	275	4
Centre for Business Strategy and Procurement, The Birmingham Business School, Birmingham City University, Birmingham, United Kingdom	4	126	5
Faculty of the Built Environment, University of New South Wales, Sydney, Australia	2	105	6
School of the Built Environment, University of Salford, Manchester, United Kingdom	3	88	7
Unisa Stem, Scarce Resources and Circular Economy (SCARCE), University of South Australia, Adelaide, Australia	2	72	8
School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan, China	2	54	9
The Bartlett School of Construction and Project Management, University College London (UCL), London, United Kingdom	2	46	10
School of Management, Jilin University, Changchun, China	2	45	11
Faculty of Science and Engineering, University of Wolverhampton, Wolverhampton, United Kingdom	2	44	12
School of Engineering and Technology, Central Queensland University, Sydney, Australia	2	25	13
School of Future Environments, Auckland University of Technology, Auckland, New Zealand	2	5	14

5.1. CSC enables ICT and digital technologies and DT as an integrator

This section identifies the current deficiencies in adopting the predominant technologies in CSC and investigates possible opportunities DT presents to tackle these challenges. Therefore, it aims to examine the incorporation of DT with the technologies introduced in the first CSC overarching theme (Table 1) that are, in fact, widely used in CSC processes. This section explicitly seeks technological junction areas in CSC where DT can be integrated with other digital and ICT technologies to enhance organisational collaboration and integration among project members and, thus, the overall performance [50–52].

5.1.1. Digital twin and blockchain

Current CSC practices have faced significant challenges, including fragmentation, poor flow of information and products, low traceability, and lack of real-time information [53,54]. On the other hand, the adoption of advanced construction methods such as Off-Site Construction (OSC) and robotic construction that can reduce construction time and waste more heavily rely on addressing these challenges due to

Table 4
Countries, their rankings, number of citations and documents.

	Documents	Citations	Ranking
United Kingdom	29	1732	1
Hong Kong	9	873	2
Australia	22	668	3
China	13	628	4
Canada	3	195	5
Portugal	2	174	6
United States	9	160	7
Singapore	3	94	8
India	3	47	9
Denmark	2	37	10
Brazil	2	30	11
United Arab Emirates	2	29	12
Malaysia	4	15	13
New Zealand	3	5	14
Nigeria	2	4	15

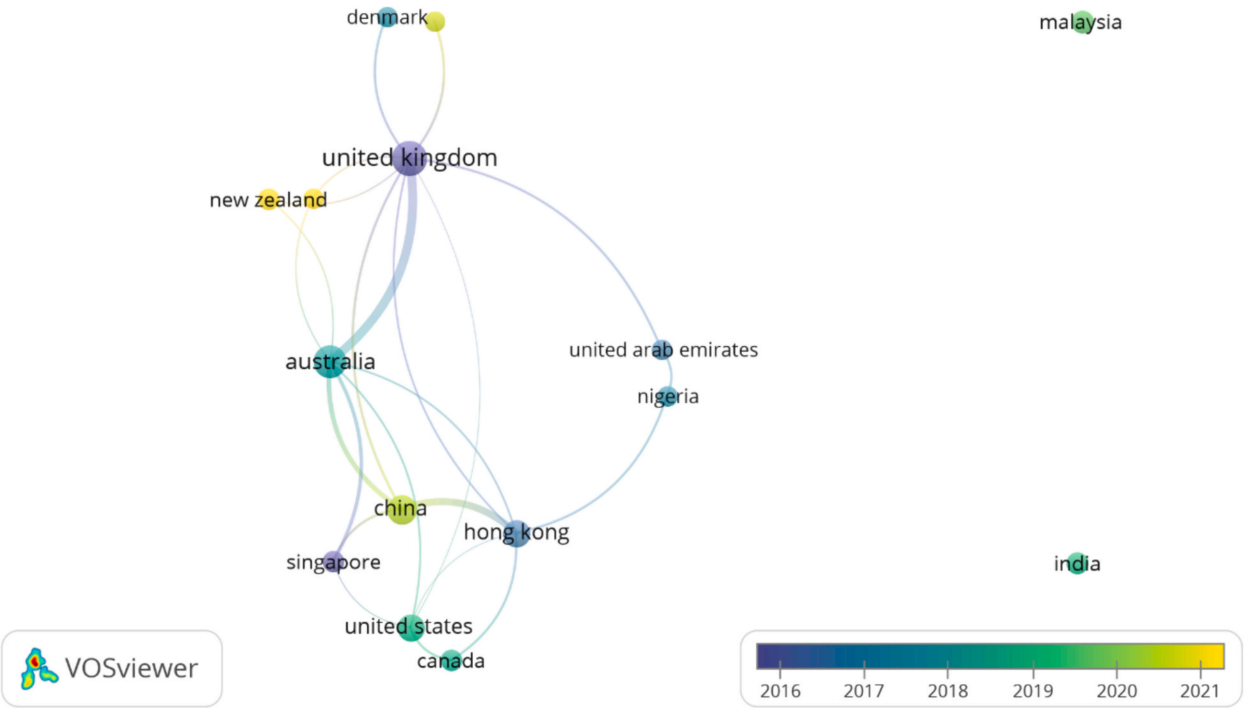

Fig. 9. VOSviewer analysis of network of countries/regions.

various parties involved in their supply chain, requiring an even more effective flow of information and products and collaboration among them compared to traditional methods [55]. Blockchain can address these challenges by improving time management, collaboration efficiency, and supply chain processes, eliminating the need for authenticity verification and enabling automated procurement and payment [56], making processes more transparent and traceable [57].

5.1.1.1. Challenges and deficiencies.

However, limited scalability [58] and the blockchain's reliance on being integrated into a comprehensive management and operational system where it can utilise blockchain-provided real-time input data from assets and processes as feed to perform elaborate CSC evaluation and optimisation tasks for stakeholders in a virtual environment [59] are considerable challenges in reaping the data management benefits of this technology.

5.1.1.2. DT possible solutions.

Addressing this deficit, digital twin technology that visually represents real-time information of physical assets and processes using data received by embodied sensors has proven to have immense potential [15]. This technology promises quality collaboration through supporting information sharing among project stakeholders. Also, such blockchain-enabled DT systems can execute highly complex construction analyses and optimisations and provide users with the results through virtual environments in real time [2,60].

For example, Adu-Amankwa et al. [15] proposed a decentralised digital twin cycle (DDTC) model that integrates blockchain technology into a DT environment for efficient data management, information sharing, and sustainability. The DDTC model consists of three layers: the Smart Building Project Ecosystem, the Digital Twin Ecosystem, and the blockchain. The outer layer collects information about the lifecycle of construction projects using APIs, IoT devices, and RFID, while the intermediate layer hosts the DT application's user interfaces. Finally, the blockchain layer serves as a decentralised container for historical data, providing validation and traceability for stakeholders sharing critical information through DT. The blockchain system embedded in the DDTC model was aimed at enhancing trust, security, decentralisation, efficiency, traceability, and information transparency throughout construction projects' lifecycles.

However, although blockchain was found to be one of the hottest topics within CSC (Section 4.4), only a limited number of studies have investigated its practical integration with DT, with most of them dedicated to incorporating these two technologies within Industry 4.0 conceptual frameworks and models [56,61]. Thus, there is dirt of research on the real-world applications of such an integration.

5.1.2. Digital twin and smart contracts

Numerous studies have reported poor contracting protocols carried out by suppliers, contractors, and clients and the corresponding delays as a source of various deficiencies in CSC, resulting in wasting considerable time, cost, and energy [62]. In other words, the centralised nature of traditional contracts where third parties are involved during CSC processes produces trust issues and time and resource inefficiencies [63,64]. As a response, smart contracts that operate using if/then computer algorithms eliminate the need for third parties by automatically writing, verifying, and executing contracts based on the information provided by main parties [61].

5.1.2.1. Challenges and deficiencies.

The factors that will influence the adoption of smart contracts in construction projects are still vague as its implementation is still in its early stages [65]. However, challenges like intricacies and inflexibilities in defining unpredicted conditions, unsophisticated analysis tools, and low processing capabilities have begun to be revealed as the major shortcomings this technology faces [66].

5.1.2.2. DT possible solutions.

As a response, a sophisticated DT system can generate digital replicas of any physical assets as subjects of CSC contracts and ascribe financial and legal parameters to these digital models that can be used in advanced analysis enabled by the process simulation capabilities of DT. Subsequently, the information derived by such analysis can be employed to predict possible scenarios that can occur over CSC, and the predictions can be included in the form of if/then codes to smart contracts algorithms. Automating such processes in an overarching DT system can help maintain the benefits of using smart contracts in CSC while addressing the shortcomings.

Hunhevicz et al. [67] suggested linking digital building twins with smart contracts on a blockchain to enable performance-based digital payments. Blockchain-enabled smart contracts execute encoded functions and rules based on the performance of stakeholders involved in a contract. Digital twins store sensory data in a cloud environment as digital replicas and facilitate performance simulations to provide input data for the execution stage. However, since the data stored and processed by DT cannot be directly connected to the blockchain, a back-end Oracle module is embedded to translate the data into the required formats for the transaction. A front-end Oracle module is embedded to allow stakeholders to provide input of static information about the asset. A thermal performance-based smart contract was developed in this study that employed the Ethereum blockchain and a building twin platform linked to the sensors receiving real-world building data. Defining fair and comprehensive logic for such contracts and their related business models was recognised as a significant challenge that needs to be addressed by further research.

5.1.3. Digital twin as the next generation of IoT-enabled BIM systems

The logistics industry has grown significantly over the past few decades, resulting in resources and stakeholders distributed across multiple CSC stages over a wider geographical area. This has led to several challenges, including costly transportation, poor data sharing and collaboration, and low agility. To overcome these challenges, BIM has played a crucial role by providing a digital platform that ensures an enhanced flow of information and visual representations of the process [55,68].

However, BIM, if not integrated with other advanced data gathering and management systems, has limitations in capturing real-time updates of assets and resources, as its fundamental task is to represent static models [69].

As a response, IoT has been a crucial solution for Construction Supply Chain Management (CSCM) to address the fragmentation of goods and services across different platforms. It connects sensing devices to enable real-time exchange of resource data [34]. The technology aims to reduce costs [70] and enhance responsiveness in a scalable and flexible way through its data exchange feature [71].

5.1.3.1. Challenges and deficiencies.

However, although digital representation technologies such as BIM can store, visualise, and share real-time data collected by IoT sensors and perform specific analyses based on this data, a more comprehensive system is required, given the incremental complexities of current CSC practices [72]. Such a system should perform more sophisticated analysis, simulations, and predictions based on more extensive data.

5.1.3.2. DT possible solutions.

With IoT becoming widespread in the construction industry in recent years, BIM adoption has experienced a promising revitalisation in the form of BIM-integrated cyber-physical systems [34]. As a prominent example of such systems, BIM-backed DT systems can perform operations such as simulation, monitoring, and prediction in every stage of CSC based on static BIM models and real-time data of assets and resources [73,74]. Besides, the BIM platform employed in such a system can facilitate the flow and sharing of the information extracted from these operations to provide efficient collaboration and integration among stakeholders.

For example, Lee, D. and Lee, S. [75] sought to cope with the schedule deviation risks in modular construction logistics by integrating BIM, IoT, and Geographic Information System (GIS) technologies into a DT framework. They leveraged the benefits of BIM-based DT scheduling and simulations to predict potential logistic risks across the modular CSC process. The framework was tested in a case project involving manufacturing modules at a factory, their delivery to the site using a truck, and their assembly onsite. Although merely using the module's location data in the simulations prevented considering overall supply chain coordination and logistic risks, their framework's output still offered accurate predictions of schedule deviations and Estimated Time of Arrival (ETA) regardless of traffic uncertainties.

5.2. *DT and sustainable CSC*

This section discusses DT's role in the current sustainability paradigm prevalent in the construction industry. Sustainable Construction Supply Chain (SCSC) refers to the management of material, information, and capital flows, and cooperation among stakeholders, focusing on economic, environmental, and social concerns [76–78].

According to Table 1, sustainability in current CSC studies is associated with specific keywords, including CE carbon emission, waste management, DW, and GSCM. This section thematically discusses the association between DT and these keywords.

5.2.1. *DT for carbon reduction and Green Supply Chain Management*

GSCM emphasises involving environmental thinking in SCM with all its facets and stages [79]. It is tightly associated with the sustainable supply chain notion as both primary concern environmental issues, with the implicit exclusion of social concerns from GSCM literature being the only difference between the two concepts [80]. Reducing carbon emissions is the primary purpose of green and sustainable development in the construction industry [81]. However, according to the carbon flow analysis carried out by Sun et al. [82], GSCM is a broad concept that encompasses all CSC stages. Based on prefabricated buildings' supply chains, processing of **raw materials**, **component manufacturing**, transportation, construction, and component assembly are among the most emission-intensive tasks. Assuming that publications related to transportation fall into the third CSC theme, “Logistics and Transportation,” this section elaborates on DT's contribution to reducing carbon emissions in the other tasks.

5.2.1.1. Processing raw material. Given that decisions made in the design stage significantly impact the carbon emissions generated throughout the entire CSC process, decisions on raw material selection, extraction, and processing methods are critical factors that can dramatically affect CSC sustainability [83]. In construction, raw material processing involves refining and smelting extracted materials like ores and limestone and eliminating waste [84].

5.2.1.1.1. Challenges and deficiencies. The largest proportion of the emissions, known as embodied emissions, in industrialised construction stems from resources consumed by mining and raw material processing machinery [85]. Affecting the overall sustainability of the CSC process, this implies the need to monitor input raw materials effectively and optimise them based on carbon emission rates during the raw material processing stage [86].

5.2.1.1.2. DT possible solutions. Although DT, with its efficient real-time monitoring and optimisation capabilities, has found its way into the raw material processing within the product design and manufacturing industries [87], such DT features are not examined in the same processes within the building and construction domain.

5.2.1.2. Component manufacturing. Component manufacturing is the process of turning processed raw materials, also known as raw products, into building components, involving mould cleaning and installation, reinforcement binding, concrete pouring, curing, treatment, and arrangement activities [88] for building components, which significantly influences overall sustainability. In other words, the diversity of these activities implies that they affect CSC's environmental aspects by imposing the threat of carbon emission accumulation.

5.2.1.2.1. Challenges and deficiencies. Another massive proportion of construction's carbon footprint and greenhouse gas (GHG) results from the component production stage with all its activities [89]. Accordingly, the challenge is implementing accurate and holistic monitoring and evaluation of carbon footprint and ultimately controlling and optimising the affecting parameters of these emissions across these activities [90].

5.2.1.2.2. DT possible solutions. The rich data from the multiplicity of production lines simultaneously functioning in a building prefabrication plant provides cyber-physical systems with more accurate monitoring and evaluation of the quality of the numerous activities involved based on productivity and carbon footprint emissions and optimise the organisation and scheduling for efficiency [91]. However, like the prior stage, DT has contributed considerably more to controlling and optimising components in manufacturing processes within highly product-oriented disciplines than in the construction domain.

For instance, Mandolla et al. [92] suggested a Blockchain-based DT system for the metal additive manufacturing phases of aircraft components. The system uses Blockchain as a common platform to track CAD files and control revisions' timeframe in the design phase. In the build and monitor phase, the DT-Blockchain integrated system contains and controls build operation parameters, including powder composition, machine, process, and laser. The distributed environment of Blockchain is utilised for shop operators in each phase to input any information and validate it with high transparency. External vendors and suppliers can also be securely involved in the shopping process by integrating information in the described Blockchain system. The Blockchain-based information system is linked to a DT environment to gather real-time data about the components produced during the delivery process, which authorised personnel can track and analyse.

5.2.1.3. Component assembly and construction. Building assembly and construction as the central practice in construction industrialisation have proven crucial for energy and time savings, therefore significantly contributing to achieving carbon reduction in CSC [93]. Surprisingly, compared to the previous stages, the component assembly and construction stage has received the bulk of attention through the lens of diminishing carbon emissions, probably due to the recent increasing attention towards off-site construction and prefabrication methods.

5.2.1.3.1. Challenges and deficiencies. However, reducing carbon emissions during the assembly and construction stage of industrialised construction faces critical challenges, from material and component selection and cost considerations to site management [94].

5.2.1.3.2. DT possible solutions. Considering these challenges, the potential to apply efficient simulation technologies like DT to the building assembly and construction stage has been merely explored. However, the situation is better in this stage compared to previous stages. These technologies could address these challenges by enhancing automation, monitoring site activities, and optimising material and cost based on carbon emissions.

Naboni et al. [95] devised an integrated design-to-assembly workflow using two digital twins: a design digital twin, where virtualisation of an automation workflow for performance-driven design is conducted, and a production digital twin, where the whole assembly production is simulated. They created a prototype of a reversible timber structure using this workflow, which involved simulating the entire assembly production. The prototype demonstrated a seamless connection between the optimised design solutions and the robotic assembly, proving the effectiveness of the workflow. The workflow has the potential to be an effective production digital twin with collaborative capabilities to deal with uncertainties during the assembly process.

Similarly, Brilakis et al. [96] proposed a Digital Twin Construction (DTC) framework that uses automated data acquisition from a construction site and CSC to create a closed-loop control system. The DTC information system is based on three core elements: 1- information stores, 2- information processing functions, and 3- monitoring technologies. Accordingly, the workflow consists of five core steps: model, build, monitor and interpret, evaluate, and improve. Consequently, the DTC framework comprises three primary controlling cycles: 1- model, build, monitor and interpret, evaluate, and improve cycle, 2- real-time feedback for safety and quality control, and 3- long-term feedback for design and planning. The study concluded that the DTC framework can be used as a reliable tool for making management decisions throughout the construction life cycle.

5.2.2. DT for demolition waste, waste management, and Circular Economy

Tightly tied to the sustainability idea, CE has recently gained significant attention among many industries [97]. Compared to GSCM, CE is a novel concept that aims to create closed-loop supply chain processes by transforming end-of-life products into resources that can be used in the same or other industries [98]. CE's ultimate goal as a regenerative system is to design a sustainable ecosystem where building products and resources can be continually repurposed, reducing the need for new resources [25]. Within the CSC context, CE targets designing closed-loop supply chain processes using DW practices and waste management strategies for building resources at the end of their life cycle to be turned into resource inputs for the processes [41,43,99].

5.2.2.1. Challenges and deficiencies. However, employing a holistic technology approach with the ability to function at multiple stages of construction CE, especially at waste management as the key to closing the CSC loop [100], to maximise sustainability outcomes of the CE implementation practice is lacking. Within construction CE studies, waste management is highly associated with DW as heterogeneous blends of building materials [101] such as concrete, wood, paper, metal, and insulation.

5.2.2.2. DT possible solutions. Based on the results of an empirical study conducted by [102], not only does early CE consideration during the design stage of construction projects' life cycle play an essential role in the waste reduction goal, but early CE-DT integration from this stage helps to achieve such a goal effectively. Meanwhile, addressing waste management through remanufacturing and demolition practices has attracted the attention of a large body of literature across many industries investigating DT potentials in CE [103]. However, practical research studies on developing integrated CE-DT systems are eminently limited within the CSC context. In what follows, the contribution of DT to construction CE and waste management as its key component is discussed.

Elghaish et al. [104] proposed a Circular Supply Chain-Based Blockchain that establishes a bi-directional relationship between the design process and circular supply chain. This allows designers to obtain BIM families of existing building elements and share them with other researchers. BIM families of reusable assets are created through the ‘scan to BIM’ method and exported as IFC files, making the information usable to all designers and asset owners involved. Smart contract functions are utilised to share the information among the parties and consecutively add it to an information repository. Designers use the stored information in the repository to check the availability of generated BIM families when building owners offer any building element. Lastly, the transactions concerning reusable or salvaged items sold by owners and purchased by the designers are made via pertaining smart contract functions and recorded via decentralised blockchain networks.

Chen and Huang [105] introduced a concept for construction-based remanufacturing in the construction field. The primary goal of their study was to establish a DT platform to connect construction projects' stakeholders over construction waste remanufacturing. They suggest that to address data and information exchange difficulties, their DT-based concept should include data integration, information communication features, and a decision support model. The data integration feature is achieved via data warehouse technology. Besides the demand/supply information, geographic location information is collected by GIS technology and integrated into the enterprise's data warehouse for the internal (the enterprise) and external (public and semi-public) information to be virtualised via corresponding DT functions. They suggest a more comprehensive data-sharing platform and an incentive mechanism that enhances information flow for effective communication. They also suggested using blockchain to transmit data more securely throughout the process. Lastly, information and analysis modules were considered the major components of their decision support model integrated into the DT platform.

Similarly, Su et al. [106] proposed a DT-based conceptual framework for Building Demolition Waste (BDW) trading and a real-life case study. In their framework, four significant services, including DT-enabled demolition strategy, DW estimation, trading mechanism, and waste delivery management, are offered via two essential tools embedded in the DT system, including data collection and data analysis and display tools. They suggested using various technologies such as GPS, RFID, LiDAR, drones, and visualisation technologies (BIM, virtual reality, and industrial cameras) to create a real-time BDW system. They also recommended using an online transaction processing (OLTP) system and an online analytics processing (OLAP) system to analyse current and historical data and assist users with decision-making. Finally, they developed a real-life case study integrating robotics, IoT, big data, and 3D printing technologies to verify the technical aspects of their framework.

5.3. DT for forward and reverse logistics

Logistics (or FL) and RL were the two main hotspots in the CSC transportation theme (Table 1). FL and RL are complementary activities within the construction transportation field with substantial impact on crucial aspects of a CSC process, including customer service levels and economic and environmental performance, by minimising the leak of energy and resources across the process [44,107]. This section discusses their definitions, challenges, and DT-provided solutions.

5.3.1. DT for transportation in Forward Logistics

FL in CSC essentially involves effectively planning, organising, and coordinating resources, materials, equipment, and workforce to ensure seamless movement and delivery of goods and services from suppliers to construction sites [108].

5.3.1.1. Challenges and deficiencies. Currently, FL practices in CSC are dealing with several challenges, such as 1) clash analysis and location optimisation [109], 2) Communication, interaction, and decision-making [110], 3) Inventory planning [111] and 4) Schedule planning [107].

5.3.1.2. DT possible solutions. Seeking DT's contribution to tackling these challenges, this review found that rather than the building level, a great deal of attention is directed towards dealing with similar issues in city [112] and infrastructure [113,114] levels within the broad context of the built environment.

In one of the limited examples, Lee, D. and Lee, S. [75] developed a DT framework for FL processes in modular construction using DT's real-time monitoring and simulation capabilities to minimise schedule deviations. Their framework includes three components: 1- physical space, 2- virtual space, and 3- FL simulation. It collects real-time data on the location of modules through IoT sensors, generates virtual twins of the modules with the help of BIM, and employs accurate simulation to detect potential transportation risks throughout the FL process, selecting the optimal route using what-if analysis and offering different alternative routes based on evaluations of other factors, e.g., time and transit permission. The results of their case study showed that their framework can predict various risks involved in the FL process and provide accurate Estimated Time of Arrival calculations.

In another case, Greif et al. [115] proposed a model for decision-making during the FL process of CSC that uses DT to reduce costs and improve efficiency. Their DT-backed Decision Support System (DSS) allows real-time monitoring of the silo's fill levels, generates assignment proposals for pickups, deliveries, and replenishments, and visualises truck routes based on accepted or modified assignments. The model also features an operational interface for customer insights, communication, and interaction. Overall, the proposed IT features of DT enable effective tracking of material silo fill levels, inventory-related logistics, and simulation capabilities to determine the best possible delivery and replenishment routes at construction sites.

At the city level, Abhilasha et al. [107] presented a DT model architecture to monitor city corridors' traffic and environmental performance measures, e.g., energy consumption and vehicular emissions. They utilised raw traffic data captured through a video detection and processing method as input data for a Real-Time Raw Data Processing Module. The processed data is used for real-time data-driven simulation to estimate and visualise energy/emission, travel time, and speed metrics.

At the infrastructure level, Zhou et al. [113] devised a conceptual DT model for large-scale railway infrastructure systems that includes six layers: 1- asset, 2- integration, 3- infrastructure, 4- function, 5- visualisation, and 6- interaction. The model aims to address the communication and interaction between railway subsystems. The asset layer provides models of all assets from industrial suppliers, while the integration layer imports and integrates them into a common platform. The infrastructure layer hosts a data bank, simulation module, and communication services. The function layer manages simulation flows, while the visualisation layer merges spatial and non-spatial information to provide users with a virtual environment. Lastly, the interaction layer establishes and assures the interconnectivity of the platform, including user interaction.

5.3.2. DT for transportation in Reverse Logistics

Closing the CE loop in construction [116] RL is a crucial aspect of CSC processes. It involves planning, implementing, and controlling the delivery of raw materials, finished goods, and corresponding information and services from where they are consumed to their origin for reuse or disposal [107,117]. Although RL is a newer idea than logistics due to the recency of the CE concept in construction, they have similar processes in common.

5.3.2.1. Challenges and deficiencies. Despite being integrative practices to a holistic logistics approach, RL grapples with challenges almost similar to the ones in FL practices in the construction industry (Section 5.3.1), for both of them require effective management of the transportation of material between multiple sources and sites.

5.3.2.1.1. DT possible solutions. In general, leveraging opportunities presented by Industry 4.0 can significantly benefit RL practices in terms of time and process assessment [118]. However, despite having many challenges in common with FL, more attention should be paid to the opportunities DT provides to deal with these challenges in RL. In addition to elaborating on one of the limited examples of such studies, what follows includes a detailed investigation of relevant research in the manufacturing domain that attended to similar challenges by benefiting from DT, with its knowledge being transferrable to the construction realm.

Züst et al. [119] created a DT model of excavation and demolition material flow, which assists local authorities in implementing new curatorial management strategies. The DT model offers the optimal path among four post-treatment RL kinds, Reuse, Remanufacture, Recycle, and Dispose, by predicting the system dynamics in a given situation. To create reliable replicas of the system's current steady state, they designed their DT in such a way that it could conduct a multi-agent simulation based on a combination of state-of-the-art methodologies, e.g., economic decision models and stochastic programming. The simulation process in their model is implemented according to the Monte Carlo method for different material flows to be quantified based on location parameters. The model could consider technical, legal, and fluctuating market price regulations. Fed by information regarding two input material types: 1- bound materials and 2- unbounded materials, and four output material types: 1- contaminated excavation, 2- uncontaminated excavation, 3- concrete DW, and 4- mixed DW, DT makes the mentioned predictions for decision-making. As a generic model, their decision-making approach could be broadly applied to different geographical regions with their specifications.

In manufacturing, Sun et al. [120] discussed using digital RL twin as a key sustainability enabler of Industry 5.0 in manufacturing. The digital RL twin is defined as a data-based digital representation of a real-world RL system, which forms a multi-architecture and high-level integrated information platform by integrating different stakeholders, data, and analytical tools to support various proactive and/or reactive decisions. Their framework comprises three layers, including the physical system layer, the cyber-physical layer, and the smart analytical layer. The first two layers collect, treat, and process the data received from the physical entities and processes. The third layer interactively provides RL decisions using AI, optimisation, and simulation models. Plus, to this systemic approach, a product-oriented approach is employed within this DT framework so that every DT model created for individual entities carries the required data for various RL activities**.** The article also discusses the implementation of this concept and its corresponding network decision optimisation in designing a compressor remanufacturing network of refrigerators from 16 cities in Norway as a proof of concept.

5.4. DT as the key enabler for efficient construction

Prefabrication and lean construction are two closely connected terms in construction strategies (Table 1). Both techniques aim for productivity through efficient use of time and resources during the construction stage of CSC [121]. Prefabrication involves designing, producing, and assembling building elements offsite for efficient and fast construction of permanent structures [122,123]. On the other hand, lean construction, as a comprehensive construction strategy, is defined as a production management-based approach to delivering construction projects [124]. As a comprehensive strategy, lean construction focuses on customer needs, minimising delays and waste, optimising work and material flows, and promoting collaboration and integration among all stakeholders [125].

Upon reviewing the studies in the previous sections, it is evident that a substantial deal of literature on the aspects and stages of CSC is based on the supply chain of prefabricated buildings, either explicitly or implicitly. To avoid redundancies and provide more up-to-date insights into efficient construction practices, this section delves into the integrated lean prefabrication approach that has gained significant attention in recent years as a strategy to enhance construction efficiency.

5.4.1. DT for lean prefabricated construction

Given their many shared objectives, prefabrication and lean construction can benefit CSC projects synergistically in terms of on-time project delivery [126], cost reduction [127], and environmental sustainability [128] Lean Prefabricated Construction (LPC) as a novel construction method that represents such synergy has palpably gained momentum in recent years due to the increasing focus on energy and efficiency criteria in the construction industry [129].

5.4.1.1. Challenges and deficiencies. However, integrating prefabricated construction, which adheres to strict criteria, into a lean construction strategy with specific standards and objectives can lead to more supply chain complexities if not supported by sophisticated and adaptable process plans, hindering the optimal workflow [129]. Considering research gaps identified in previous studies in this domain, this paper concludes that the fundamental challenge in implementing LPC is the insufficient flexibility against complexities and uncertainties associated with the prefabrication supply chain. To ensure the success of planned tasks, team leaders should stay updated on the progress of operations, receive feedback on decisions, and have the flexibility to make changes to daily functions in consultation with the parties involved [130].

5.4.1.2. DT possible solutions. As a solution, a DT-backed LPC system enables translating lean construction principles into production planning and control simulations fuelled by ML algorithms to provide construction planners with optimised decision-making processes according to the changing conditions of an ongoing project [131,132]. However, there is a relative shortage of theoretical and practical research works aiming to integrate DT with LPC practices compared with the studies on DT adoption in lean construction or its integration with prefabrication.

Abideen et al. [133] introduced a DT-based reinforced learning framework for supply chain and logistics that incorporates lean thinking to achieve agile and flexible decision-making. Their framework involves the use of real-time simulation modelling. This is achieved using IoT-assisted real-time data fed into the simulation models, aiming to generate patterns of occurrences or scenarios in response to supply chain and logistic complexities. Their model also focuses on how these real-time data patterns can be recorded to teach a machine learning algorithm to behave and function as a reinforced or prescriptive learning platform. The framework has contributed to enhancing supply chain and logistics decision-making under the overarching theme of Industry 4.0.

Moreover, such systems can utilise similar simulation capabilities to enhance production flexibility by adapting to uncertainties specifically through efficiently allocating workforces in real-time so that prefabricated buildings not only can meet lean waste reduction criteria but can fit their client's needs [134].

Zhuang et al. [135] used Digital Twin (DT) technology in the prefabrication production stage to monitor and predict shop-floor operations. They employed real-time visualisation and simulation capabilities of DT along with the learning mechanism of the Markov chain as the underlying model to provide the staff with accurate and timely decision-making when production exceptions occur. They developed an engineering case study to verify the practicality of their framework and promote DT applications in the production stage. The study achieved a 97% model integrity rate of each resource in the generated Shop-floor Digital Twin (SDT) and 95% consistency between SDT and the physical shop floor. They found that there was only a three-second time delay between the two.

5.5. *DT applications in construction supply chain management*

The CSCM theme in this review contains three hotspots, including collaboration, project management, and integration (Table 1). Initially aroused and adopted in the manufacturing domain, supply chain management is a holistic approach to managing the network of organisations involved in the processes, targeting the production of goods and services by stakeholders for end customers [136]. The primary aims of SCM are to increase customer value and decrease business [137]. To achieve these goals, researchers and industry experts have attempted to apply the concept of SCM in the construction industry, termed CSCM [3], which primarily involves the management of information, flow, and money in the CSC network that unites different types of related information in construction activities, with the management of building materials being the most intrinsic. [138].

However, in contrast to the manufacturing industry, which embraces repetition as the key to efficiency, the cardinal concern regarding implementing an efficient CSCM is process fragmentations and discontinuities due to various scattered internal and external project stakeholders involved [139]. In the following section, with the apparent assumption that project management is an intrinsic concern to construction management projects, the present review investigates the rest of the CSCM hotspots identified in Sections 4.4, namely collaboration and integration, as significant contributors to combating the pivotal CSCM challenge mentioned. Plus, it explores DT-offered solutions to tackle these concerns.

5.5.1. *Integration and collaboration in CSCM*

Because of CSC's fragmented nature, there has invariably been a constant effort to overcome shortcomings of inefficient relationships between parties involved in traditional supply chain practice, lack of trust, and thus lack of productivity by achieving more integration within the CSCM field [35]. Collaboration is a relatively more contemporary term in the industry, initially gaining popularity in manufacturing [140]. Inspired by the manufacturing industry, the construction industry has gradually shifted from scattered traditional communications towards collaborative interactions to achieve more integrated supply chains and ultimately restrain systemic problems [141].

5.5.1.1. Challenges and deficiencies. However, many studies have highlighted the need for employing an elaborated common information system serving as a convenient yet inclusive data-sharing platform for different stakeholders in CSC, especially for more complex projects [142]. Such a system is required to enable a seamless flow of traceable, transparent, and accurate information [143] and offers flexible decision-making features [144] as a significant barrier in adopting integrated and collaborative CSCM.

5.5.1.2. DT possible solutions. DT, as investigated in Section 5.1, has also proven to have remarkable potential for data and information management in different processes involved in supply chains across many industries.

Integrating Distributed Ledger Technology (DLT) within a DT environment can not only fulfil the need for trust in participants using permissible distributed ledgers but also increase traceability, integrity, and transparency of information flowing between CSC physical assets and processes and permitted parties and among the parties themselves through real-time bi-directional communications [145].

Likewise, in the manufacturing industry, DT environments, along with blockchain as its data management module, have proven their potential to provide stakeholders with a decentralised peer-to-peer data-sharing platform that allows the secure flow of reliable and relevant information about a product [146].

Similarly, within the transportation field, a smart contract-supported DT information management can track and manage the transactions created in a DT environment through distributed ledgers and also to store DT-produced data and exchange them between digital replicas for AI-fuelled DT analysis and simulation functions to produce predictive analytics and provide consensus-based decision makings about assets targeted to transportation [147].

However, theoretical and practical efforts to employ DT as a data and information-sharing tool to achieve more holistic supply chain integration and collaboration within the construction industry are less widespread than are in many other sectors. Likewise, from the building lifecycle perspective, more efforts are needed to promote DT-enabled management to achieve intelligent integration and collaboration among stakeholders [148].

Jiang et al. [149] developed a blockchain-enabled DT information-sharing platform to collaborate flexibly in modular construction production and assembly processes. They used an Integrated Domain-

Driven Design model to achieve information integration and seamless and transparent collaboration among the DTs of various domains. They proposed a smart contract workflow for controlling the fit-out operations. It comprised off-site and on-site contracts that operated automatically based on information received by scanning the modules' RFID tags. They evaluated their proposed platform on Hyperledger Fabric using a case study located in Hong Kong, proving more flexibility and scalability of their devised smart contract than traditional smart contract practices.

As elaborated in Section 5.3.1, Lee and Lee [75] introduced a DT system that allowed logistic risks to be minimised and accurate ETA of prefabricated modules to be predicted using DT simulation capabilities. In addition to those capabilities, their system features a web front and back end that uses specific plug-ins to create interactive 3D models in real-time using BIM-provided data. The Unity engine in the back end is embedded as an immersive platform for DT-enabled logistic monitoring and simulations based on input data, including BIM data, simulation parameters, and real-time logistic data collected by IoT sensors, enabling project members to collaborate through convenient real-time visual and textual information sharing. Overall, the system is designed to achieve a more integrated modular construction supply chain and boost stakeholder collaboration.

Purposed at managing construction sites, Lee et al. [150] sought to address the internally fragmented relationship among project participants by devising an integrated framework of DT, BIM, and blockchain systems to establish project-related information sharing with data traceability features. The sensors transfer the data from a construction site to a virtual environment within DT. Then, DT updates the virtual construction site by merging the transferred data and the site's as-designed BIM model. Subsequently, the as-planned BIM model is used for DT to check if a stakeholder's progress complies with its predefined tasks and corresponding standards, all of which are embedded in its related block in a blockchain network. The blockchain network only stores and shares compliance statements as essential data for an accountable collaboration in the framework.

6. Conclusions

This study explored the applications and potentials of DT in addressing the challenges faced by the construction industry, with the ultimate goal of achieving integration and efficiency during the CSC processes. The researchers conducted a five-phase MMLR involving an SLR strategy, which incorporated two quantitative and one qualitative stage, accompanied by two supplementary qualitative investigations undertaken in discussions. The MMLR effectively addressed the research questions, providing synthesised information for answering each question based on the results achieved in previous questions.

In a nutshell, based on the SLR strategy, relevant data around CSC was collected using the Scopus database (Phase 1). Then, the collected data underwent a bibliometric analysis utilising VosViewer to extract current CSC hotspots as keywords (Phase 2). In the last stage of the SLR, the quantitative approach started with interpreting and refining the extracted keywords and subsequently classifying them into overarching themes (Phase 3). Afterwards, the quantitative approach continued thematically searching for the keywords through the construction literature to find the main challenges around each keyword (Phase 4). In the last stage of the qualitative approach, DT-provided solutions for the identified challenges were investigated through discussions within the construction and other industries literature, e.g., manufacturing and aerospace (Phase 5).

Regarding findings, the SLR strategy identified hotspots such as blockchain, sustainability, logistics, prefabrication, and collaboration. At the same time, the discussions revealed a wide range of challenges around them, from insufficient integration of ICT technologies with CSC processes and monitoring carbon emissions to real-time clash analysis and inflexibility of LPC practices. Consequently, further discussions on DT-provided solutions to the discussed challenges led to discovering potent capabilities demonstrated by DT in integrating ICT and digital systems, such as IoT and BIM, which can establish real-time, bi-directional communications with AI, such as machine learning and reinforced learning, tasked with accurate data evaluation and process optimisation over CSC. Additionally, the findings showcased existing adoptions of DT in the construction industry and translatable examples of using DT in other industries to achieve sustainability goals, e.g., optimising the processes based on carbon emissions, enhanced FL and RL, e.g., minimising schedule deviations and predicting system dynamics while offering optimal paths in RL practices. Moreover, the findings demonstrated the applications and potentials of DT-backed LPC practices to reach agile and flexible decision-making, along with capabilities offered by DT-enabled CSC management to foster integration and collaboration.

Moreover, while conducting the co-authorship analysis, it was uncovered that there is a lack of sufficient scientific collaboration at the institutional and country levels. At the institutional level, although a relatively high number of institutions have contributed to the CSC knowledge, the absence of links between institutions implies that the research in the field is predominantly performed independently within individual institutions. At the country level, the analysis suggested that there still exists a substantial scientific gap between countries since some countries have a solid background in knowledge production and exchange while others have paid very limited attention to generating CSC-related knowledge, whether independently or collaboratively. Consequently, the findings emphasise that not only is more collaboration required in CSC practices, but there is also an urge for co-authorship to exchange knowledge in the CSC field.

6.1. Research significance

Due to its complex nature, the construction industry has embraced DT more slowly than other industries. However, in recent years, the industry has experienced significant growth in DT adoption, resulting in various benefits such as real-time process monitoring, improved stakeholder collaboration, and enhanced decision-making performance. To reap the full DT integration and collaboration capabilities in construction, researchers and experts should adopt it across the entire CSC rather than in isolated stages. However, there is a shortage of theoretical and practical studies on such an adoption. This review explores DT's current applications and potential to deal with significant CSC challenges, providing a fertile ground for researchers to develop frameworks to target CSC-specific challenges purposefully. Also, from a practical lens, this study not only identifies current technological and organisational bottlenecks and challenges within and between different CSC stages but by scrutinising examples of DT adoption in other industries to overcome similar challenges, it provides valuable insight for construction experts and practitioners to address these challenges.

6.2. Research limitations

The present study is one of the rare examples of extensively investigating DT in the whole CSC process. However, considering DT as a sophisticated technology functioning with multiple enabling technologies at multiple system layers on the one hand and CSC as a broad context involving various construction stages undertaken by various stakeholders on the other hand, conducting a thorough study on DT for every CSC aspect and stage was beyond content limitations of standard article formats. Moreover, using Scopus as the only database and Review papers as the only document type for searching for CSC concerns can result in better search performance and a higher probability of extracting more validated concerns. Still, it may also lead to overlooking some less frequent yet emerging concerns.

6.3. Recommendations for future studies

While searching for current CSC challenges (addressing RQ2) and the ways DT contributed to these challenges (addressing RQ3), the authors found knowledge gaps or a dearth of studies in some specific areas in this review, including 1- implementation of smart contracts in construction projects, especially in CSC practices 2- DT adoption in raw material processing in construction 3- DT adoption in component manufacturing in construction 4- DT adoption in component assembly processes in construction 5- practical research around developing integrated CE-DT systems in construction 6- DT adoption in FL and RL practices at the building level, rather than city level 7- DT integration with LPC 8- theoretical and practical efforts to employ DT as an information-sharing tool in construction 9- DT-enabled data management among stakeholders in construction. Addressing these gaps by investigating other industries to explore how they utilise DT to tackle similar challenges (addressing RQ4), this study provides ample opportunities for researchers to further bridge the gaps by developing frameworks and prototypes identical to those of other industries yet contextualised and construction-based.

Although this review recognised specific challenges around CSC single stages and hotspots, it strongly suggests holding an integrated CSC approach to combat these challenges in future studies. Even with exploring DT capabilities to deal with these challenges, this study highly recommends considering applying these solutions in a way that the applications could be linked to comprehensive DT-backed CSCs in later theoretical or practical attempts, even if they are planned to be adopted in single CSC stages. This suggestion stems from process fragmentations and discontinuities and, consequently, a perceptible need for integration in current CSC studies and practices that have suffered the construction industry. As a specific yet notable suggestion, considering the increasing demand for sustainable construction, carbon reduction through GSCM can be regarded as one of the pivotal CSC concerns that suffers clearly from lack of such integration, implying it to be an essential topic for future studies.

In future studies, it is preferable that researchers undertake inter-organisational and international research to ensure an insightful and balanced exchange of CSC-related knowledge. Thus, CSC challenges like process fragmentation can be effectively addressed, and global CSC impacts can be controlled.

CRediT authorship contribution statement

Sajjad Bakhshi: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ali Ghaffarianhoseini:** Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Amirhosein Ghaffarianhoseini:** Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mina Najafi:** Writing – review & editing, Methodology. **Farzad Rahimian:** Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Chansik Park:** Writing – review & editing, Methodology, Formal analysis. **Doyeop Lee:** Writing – review & editing, Methodology, Investigation, Data curation.

Declaration of competing interest

The author(s) declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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