Digital Twin in Prefabricated Construction – Approaches, Challenges and Requirements

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Abstract –

Digital Twin (DT) is a virtual replica that mirrors physical objects, systems, or entities. In the construction sector, DTs play a crucial role in building management, optimizing energy usage, predicting maintenance, and enhancing building lifecycle management. Although effectively integrated into traditional construction practices, its application in the prefabricated construction (PC) field remains relatively limited. Despite its potential to transform the PC, a significant research gap exists in comprehensive literature addressing the approaches, challenges, and requirements specific to this field.

This study aims to bridge this gap through a mixed-method research approach that includes bibliometric analysis and systematic review. Publications related to PC and DT are collected from the Scopus database, followed by bibliometric analysis to offer a quantitative insight into the current research trends, prolific authors, and geographical distribution. Furthermore, this study conducts a systematic review that qualitatively analyzes the objectives of DT applications in PC, explores its methodological approaches, identifies challenges and recommendations for practitioners and researchers, and suggests future needs. The findings highlight the pressing need for standardization, robust data management, and scalable solutions to navigate the complexities. Conclusively, this paper presents a comprehensive conceptual framework to facilitate the application of DT in various phases of PC. The critical limitation is the reliance on the publications on the Scopus database and its potential biases. Excluding the need to expand on more emergent publications, discussing empirical DT studies in PC to highlight interoperability and standardization needs is also required for future research.

Keywords –

Prefabricated Construction; Digital Twins; Cyber-Physical System; Building Information Modeling; Internet of Things

1 Introduction

Traditional construction (TC) methods have faced criticism for low productivity, delayed project completion, unskilled workforce, subpar performance, and inefficient resource management. In response, prefabricated construction (PC) has emerged as a contemporary construction method, gaining popularity for its efficiency and benefits [1]. Though PC's origins trace back to the 1960s, its recent surge is primarily attributed to advancements in computing and technology like Building Information Modeling (BIM), Artificial Intelligence (AI), and the Internet of Things (IoT) [2]. BIM, in particular, is widely adopted in PC to address issues such as the need for early design decisions, logistical and supply chain complexities, and inadequate collaboration among stakeholders. As a digital representation, BIM encompasses a facility's physical and functional characteristics, serving as a shared and comprehensive knowledge base for information [3]. This information provides a dependable foundation for decision-making throughout the building's life cycle, from the initial concept stage to eventual demolition [4].

Using the cyber-physical system (CPS), Digital Twin (DT) is gaining significant traction across various industries, involving real-time monitoring, performance optimization, predictive analysis, simulations, and testing to aid critical decision-making processes. DT is emerging as a pivotal technology in the Industry 4.0 era, finding integration across diverse sectors. It essentially creates a digital replica or model of a physical entity (known as the physical twin), with both entities being interlinked through real-time data exchange [5]. This concept allows the Digital Twin to accurately reflect the state of its physical counterpart in real-time, and vice versa. DT's applications are varied, encompassing real-time monitoring, design and planning, optimization, maintenance, and remote operation [6]. Initially developed in the aerospace sector, DT is now poised to transform other industries, including manufacturing, construction, and healthcare [5]. By bridging the physical and virtual worlds in real-time, DT offers an accurate approach to modeling complex, unpredictable scenarios. This ability, especially when combined with BIM, significantly improves and addresses PC challenges. Given BIM's interaction with CPS, DT is seen as a mature evolution of BIM [7].

Although DT was initiated in product lifecycle management by Michael Grieves in 2002 [5], its significant existence in construction began in the 2010s and the early 2020s in PC, as the technology matured in managing complex construction projects became more evident. However, those are related to the application rather than the overview of DT in PC, and a critical gap exists. To address this gap, this study aims to bring out the following objectives: (1) scientometrically analyze the status of DT application in PC; (2) understand the level of DT integration and approaches in PC; and (3) identify the challenges and their requirements. To achieve these objectives, articles searched from the Scopus database are analyzed bibliometrically and systematically.

2 Digital Twin in PC

2.1 DT in Construction

With the rise of IoT, which is the application of unique identifiers to physical objects that enable them to be connected to a network, allowing the transfer of data to and from those objects, the application of DT in the construction field is increasing. The evolution of various AI and machine learning (ML) technologies has made it even more possible in recent years [8]. From the articles published in the Scopus database, Figure 1 depicts a sharp rise in DT across industries from 2009 to 2023. A modest start with a few yearly publications until 2016 precedes a significant surge from 2017 onward, indicating increasing adoption of DT technology. The numbers more than double annually, from 38 in 2017 to a projected 2866 in 2023, highlighting the rapidly growing integration of DTs in the era of Industry 4.0.

In the construction sector, the application of DT has been increasing in the past few years. This can be depicted in Figure 2, which presents the distribution of articles between the engineering and construction sectors from 2014 to 2023. While engineering publications have grown substantially, reaching 1944 in 2023, DT in PC has also seen a notable increase, constituting approximately 15% of the engineering total. This percentage underlines the rising significance of DT applications in construction.

Initially, DT usage in the construction sector predominantly focused on post-construction operations and maintenance [9]. However, advancements in AI and IoT technologies have expanded DT applications to include logistics, supply chain management, design simulation, and energy optimization through sensors and machine learning. In PC, the synergy of DT with BIM is increasingly recognized for maximizing efficiency and promoting sustainability [10]. Some predominant applications include streamlining design, manufacturing, and assembly processes and improving lifecycle management through real-time data analysis and simulation. While many articles have addressed DT applications across PC phases, a thorough overview of DT applications is limited. For instance, Xie and Pan (2017) explored practices and challenges, proposing a basic framework for DT's integration with PC [9]. Yevu et al. (2023) reviewed DT in PC, focusing only on supply chain and carbon emissions [11], while Zhuo et al. (2023) discussed all digital technologies in PC [12]. This indicates the need for a more holistic review of DT applications in PC.

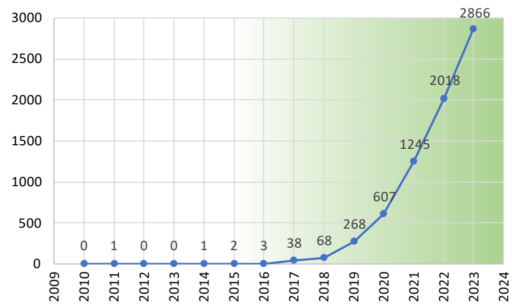

Figure 1. Application of DT over the years

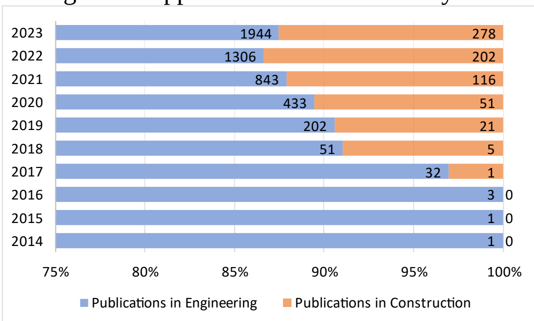

Figure 2. Percentage of publications in engineering and construction

2.2 Fundamental Components of DT in PC

The fundamental components of a DT in PC include:

- **Physical assets:** The PC components, such as panels, modules, or entire building sections, are the core objects that the DT will replicate.
- **Data collection system:** IoT sensors and devices embedded in the components gather real-time data on performance, conditions, and usage [13].
- **Connectivity system:** A network infrastructure enabling continuous data transmission from the physical to the digital, often utilizing cloud computing.

- **Digital replica:** A virtual model, usually created using BIM software, that reflects the physical characteristics and behavior of the PC components.
- **Data processing and analytics:** Software systems and algorithms that analyze the data collected incorporating AI and ML for advanced insights [11].
- **Integration layer:** Middleware that facilitates the integration of the DT with other systems, such as BIM, ensuring cohesive data flow and functionality.
- **User interface:** A dashboard to visualize data, interact with the DT, and make informed decisions based on the insights provided [9].
- **Simulation and modeling tools:** Applications to simulate various scenarios on data collected, predict outcomes, and plan for future actions in the virtual world.
- **Feedback loops:** Mechanisms that allow for the information and insights gathered from the DT to be fed back into the design, manufacturing, or construction process to improve future PC projects.

The integration of DT differs significantly between TC and PC. As mentioned earlier, DT in TC primarily focuses on managing on-site activities and adapting to changing project conditions, thus enhancing project management and resource allocation [14]. Conversely, in PC, DT is applied to optimize factory-based manufacturing, logistics, and assembly processes, benefiting from a more controlled and systematic environment, thus leading to improved precision and efficiency. Building on this foundation, Sections 3 and 4 delve into DT's detailed application in PC, highlighting empirical studies and integration strategies for overcoming identified challenges.

3 Research Approach

This study adopted a mixed review approach [4] that integrates a bibliometric analysis and a systematic review to mitigate biased conclusions. Bibliometric analysis is a quantitative research method to explore the patterns, trends, and impact within a body of literature. It involves statistical analysis of articles' metadata to understand the development and dissemination of knowledge in a specific field. On the other hand, a systematic review is a methodical and comprehensive literature review focused on a particular research question. It aims to identify, evaluate, and synthesize all available research evidence relevant to that question. Figure 3 illustrates the three-step methodology sequentially adopted in this research. As a first step, the Scopus database, known for its extensive coverage and stringent peer review process [4, 9], was selected as the primary source for literature retrieval. This search was confined to English-language articles, specifically targeting journals and conference proceedings in the Engineering subject field. The research focused on a set of keywords intertwining DT and PC, encompassing terms such as "digital twins," "virtual replica," "predictive twin," and various related phrases in prefabrication such as "prefabricated construction," "prefabricated structures," "modular construction," "precast construction," "offsite construction," "modular integrated construction," "ppvc," "industrialized construction," using the Boolean operator "AND." The initial search yielded 79 articles, providing extensive bibliometric data. However, not all are aligned with the study's focus. After thorough abstract and full-text reviews, 47 articles are included in this study.

Subsequently, VOSviewer, which facilitated the construction and visualization of a comprehensive bibliometric network, was employed for a bibliometric exploration, concentrating on the co-occurrence of keywords and the geographic distribution of publications. Finally, the publications were thoroughly examined to analyze the objective-oriented application, methodological approaches, challenges, and requirements, and a conceptual framework was devised to facilitate the application of DT in PC.

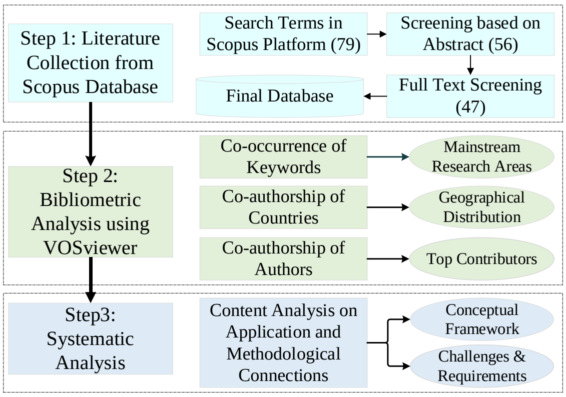

Figure 3. Research steps and approaches

4 Analysis and Discussion

This section delves into the bibliometric content analysis and discussions based on the final dataset derived from step 1, as outlined in Figure 3.

4.1 Bibliometric Analysis

The bibliometric analysis concentrates on three aspects: discerning main research themes via keyword co-occurrence, mapping global research through country co-authorship, and identifying leading contributors through author co-authorship networks. This approach provides insights into the development, geographic distribution, and critical DT and PC research contributors.

4.1.1 Research Themes

The "co-occurrences of keywords" analysis is vital to identifying dominant themes and topics in DT and PC literature [4]. Figure 4 illustrates a network map that visualizes the interconnectedness of keywords based on their co-occurrence in the literature. Central to the network is “digital twin,” with 25 occurrences and 11 links, demonstrating a total link strength of 22. This highlights its pivotal role and frequent association with other key topics in the field. Adjacent to 'digital twin,' the term 'modular construction' features prominently, with 13 occurrences and a total link strength of 12, indicative of its significant overlap with DT concepts. The “construction industry,” with ten occurrences and a total link strength of 9, bridges multiple topics, suggesting its encompassing impact across various research themes.

Further analysis in Table 1 identifies “architectural design” and “prefabricated construction” as influential nodes within the network, having 8 and 7 occurrences, respectively. This reflects their integral relationship with DT in streamlining design/construction methodologies. BIM emerges as a crucial facilitator within the DT framework, evidenced by its six occurrences and a link strength of 6, pointing to its role in enhancing the digital representation of construction. Other notable keywords like “offsite construction,” “construction projects,” “decision making,” “modular integrated construction,” and “robotics” are featured, each with five occurrences, signifying their relevance. The link strengths and occurrences of these terms, as reported in Table 1, underscore the multi-faceted nature of DT and PC, revealing a rich tapestry of interconnected research areas.

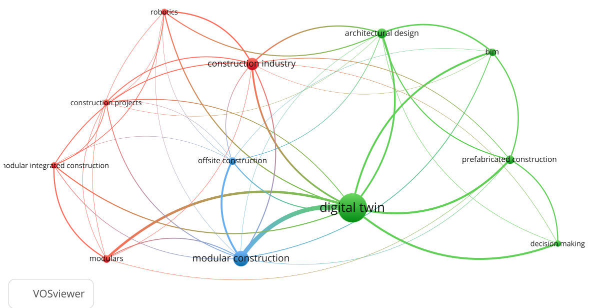

Figure 4 Network of keywords co-occurrences

4.1.2 Contributor’s Geographical Distribution

Analyzing the geographical distribution of research offers insights into DT and PC's leading research countries and the degree of international collaboration. Figure 5 visualizes the international collaboration network with a minimum of 3 articles and 20 citations, and their network details are presented in Table 2. China emerging as the most prolific contributor, with 18 publications and a link strength of 3, indicating focused research efforts within the country as of 2022. Hong Kong follows, with 9 publications and higher connectivity, reflected by 4 links and a total strength of 6, suggesting its central role in research collaborations.

Table 1. List of keywords in the network

Keyword	Occurrences	Links	Total link strength
digital twin	25	11	22
modular construction	13	10	12
construction industry	10	11	9
architectural design	8	9	8
prefabricated construction	7	7	7
BIM	6	6	6
modulars	6	7	6
offsite construction	6	8	5
construction projects	5	8	4
decision making	5	4	4
modular integrated construction	5	7	5
robotics	5	8	5

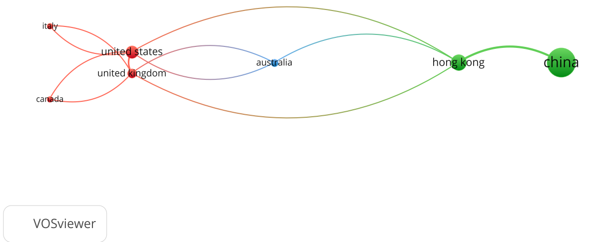

Figure 5 Network of co-authorship of countries

Table 2. Top contributing countries

Country	Publication	Links	Total link strength	Avg. year
China	18	1	3	2022
Hong Kong	9	4	6	2022
United States	7	5	6	2022
United Kingdom	5	5	6	2023
Australia	4	3	3	2022
Canada	3	2	2	2023
Italy	3	2	2	2021

The US is highlighted as a key player with 7 publications and 5 links, demonstrating its collaborative ties and a balanced link strength of 6, matching its research output in 2022. With 5 publications and 5 links, the UK continues its active research engagement into 2023, indicating an ongoing commitment to advancing the field. Although smaller, with 4 publications, Australia’s contribution indicates a strong within-country focus, as shown by a link strength of 3 in 2022. Canada and Italy, each with 3 publications and a link strength of 2, demonstrate their involvement, with Canada's activity projecting into 2023 and Italy's contributions noted earlier in 2021. These underscores DT and PC research's dynamic and interconnected nature, with varying degrees of international collaboration and research focus.

4.1.3 Top Contributors

Identifying principal authors and contributors highlights influential researchers and groups in DT and PC. This analysis underscores leading voices, offering insights into the field's key drivers. It aids in pinpointing potential collaborators and grasping the scholarly communication network. Out of 163 authors from the data collected, Figure 6 and Table 3 depict the co-authorship network among scholars in this domain with a minimum of 2 articles and ten citations. The network map reveals a robust collaborative cluster centered around Huang, George Q., Jiang, Yishuo, and Zhong, Ray Y., each with four documents to their credit, sharing six links and a total link strength of 17 in the year 2022. This trio forms a core collaborative group, underlining their significant contribution to the field.

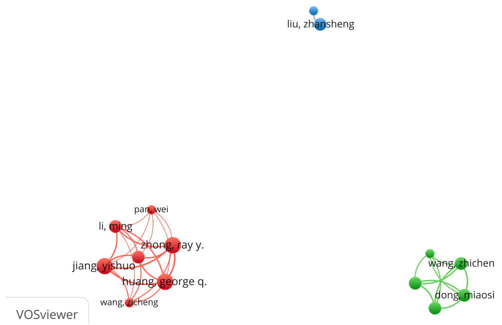

Figure 6 Network of co-authorship of authors

Table 3. Top contributing authors

Country	Documents	Links	Total link strength	Avg. Year
Huang, George Q.	4	6	17	2022
Jiang, Yishuo	4	6	17	2022
Zhong, Ray Y.	4	6	17	2022
Dong, Miaosi	3	4	11	2021
Li, Ming	3	6	13	2022
Liu, Xinlai	3	6	14	2022
Liu, Zhansheng	3	1	2	2022
Wang, Zhichen	3	4	11	2021
Yang, Bin	3	4	11	2021
Zhang, Binghan	3	4	11	2021

Adjacent nodes represent authors such as Dong, Miaosi, Wang, Zhichen, and Zhang, Binghan, each with three documents and four links, indicating active participation and a link strength of 11 in 2021. Li, Ming, and Liu, Xinlai, also with three documents but possessing stronger collaborative ties, evidenced by higher link strengths of 13 and 14, respectively, in 2022, are key figures within the network. Liu, Zhansheng, with 3 documents but a solitary link and a minimal link strength of 2 in 2022, appears as an emerging contributor within the network. The visual data from Figure 6, combined with the quantitative metrics from Table 3, highlight the influential authors and the intensity of their collaborations, offering insight into the community driving DT and PC research forward.

4.2 Content Analysis

This section delves in-depth into the objective-oriented application of DT and PC, exploring their methodological connections, proposing a conceptual framework, and dissecting the challenges and requirements to leverage DT's full potential.

4.2.1 Objective-Oriented Application

The integration of DT in PC represents a pivotal shift towards leveraging advanced digital technologies to address various challenges and objectives, such as enhancing efficiency, innovation, and sustainability. Figure 7 illustrates the spectrum of objectives in the integration of DT in PC. The paramount objective is efficiency optimization, highlighted in 17 articles, with significant contributions such as ChainPM, a blockchain 3.0 paradigm enhancing construction project management by Zhao et al. [15], resulting in a 99.8% reduction in information synchronization latency. Jiang et al. introduced a DT-enabled smart PC system for optimizing on-site assembly processes [16]. Other notable integrations include supply chain coordination [17] and immersed tunnel works [18]. These examples show a coordinated industry effort to use DT to streamline PC processes and reduce downtime, highlighting a broader trend toward increased efficiency.

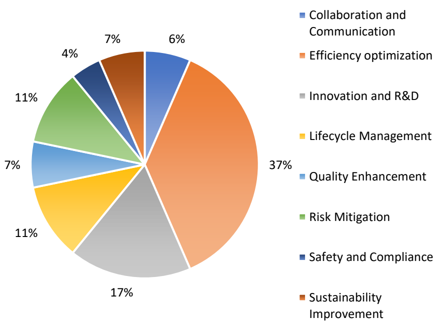

Figure 7. Distribution of objectives of DT in PC

Innovation and R&D, encapsulated in 8 articles, are represented by advances such as exploring multi-scale and multi-scenario digital twins by Jia et al. [19], underscoring the industry's endeavor to tackle complex digitalization challenges. Lifecycle Management and

Risk Mitigation are also well-represented; for instance, Nguyen et al. developed a digital engineering model combining the DfMA with object-oriented parametric modeling techniques [20]. Osadcha et al. systematically review DT geometry updating, emphasizing the need for accurate, real-time data to manage and mitigate risks throughout a building's lifespan [21]. Quality Enhancement, highlighted in works like Shi et al.'s method for geometry checking of precast culvert segments [22], 3D scanning-based geometric DT, and assembly [23], showcases the precision that DT can bring to construction quality control.

Although Safety and Compliance, and Collaboration and Communication appear less frequently, they are no less critical. For instance, Yang et al. [24] explored computer vision for fall hazard detection on construction sites. Sun et al.'s virtual reality training system based on IoT technology demonstrates DT's potential in improving safety and fostering collaboration [25]. Meanwhile, the objectives of sustainability improvement, illustrated by works such as DT-enabled prefabrication supply chain for carbon emissions evaluation by Yevu et al. [11], align with global environmental sustainability goals, showing the promise of DT in driving green construction practices. This reflects a multi-dimensional approach where DT serves as a cornerstone for innovation, addressing efficiency, safety, quality, and sustainability. As such, Figure 7 illustrates the current state of DT application in PC and points to potential areas for future research and development within the industry.

4.2.2 Methodological Connections

Integrating various technologies with DT in PC exemplifies the industry's movement toward digitalization. Exploring their methodological connection is essential to understanding how different technologies interplay with DT, enhancing PC efficiency, informed decision-making, and fostering innovation for a competitive, sustainable, and safe construction industry. Figure 8 represents the frequency of other technologies integrated with DT and PC. Among the technologies, BIM is the most integrated with DT in PC [15, 17, 20, 26], showcased by its highest occurrence. The pivotal role of BIM reflects its comprehensive digital representation capabilities essential for the life cycle management of a building [9]. Following BIM, IoT, and sensors are instrumental in real-time data acquisition, essential for the dynamic updating of DT to reflect the current state of PC elements [26-29].

AI and ML stand out as the third most integrated technology, often with BIM and IoT, highlighting their role in processing and analyzing data for predictive insights and decision-making [20, 26-29]. Conversely, augmented reality/virtual reality (AR/VR) [25], blockchain [30], cloud computing [31], finite element method (FEM) [32], robotics [26], and geographic information systems (GIS) [17] show a nascent integration. These technologies, despite their lower integration frequency, bring distinct advantages such as enhanced visualization (AR/VR), secure data transactions (blockchain), scalable data storage (cloud computing), precise structural analysis (FEM), automation (robotics), and spatial data analysis (GIS).

In conclusion, while BIM and IoT form the backbone of DT integration in PC, the full spectrum of digital technologies contributes to a more intelligent, efficient, and interconnected construction ecosystem. Each technology, irrespective of its current integration frequency, has the potential to revolutionize aspects of DT in PC, indicating a trend towards an increasingly digital future in the construction sector.

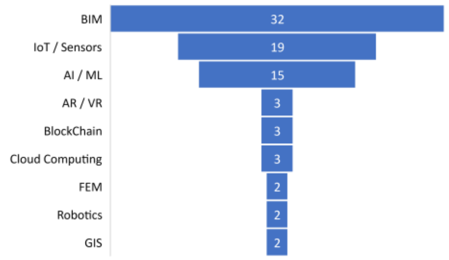

Figure 8. Frequency of other technologies in DT-PC integration

4.2.3 Conceptual Application Framework

Integrating DT into PC is a multi-stage process involving careful planning, continuous data collection and analysis, and advanced technologies like AI, IoT, and BIM. Figure 9 encapsulates a comprehensive framework for integrating DT in PC, encompassing the entire lifecycle of a structure. From initial BIM-based design to IoT-enhanced manufacturing and logistics, the framework ensures real-time data flow and optimized construction processes. The subsequent stages of on-site assembly, quality control, and operation benefit from continuous DT interaction, facilitating predictive maintenance and efficient building management. Finally, the DT supports sustainable decommissioning and material recycling, aligning with circular economy principles. This integrated approach signifies a transformative step towards intelligent, sustainable construction practices.

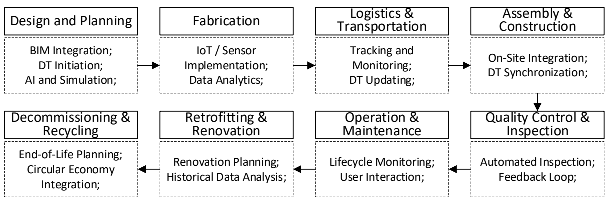

Figure 9. Stage-wise application framework

4.2.4 Challenges and Requirements

The meticulous management of extensive data is a formidable challenge in DT-PC integration, necessitating unwavering accuracy, uniformity, and instantaneous updates [8]. Thus, ensuring data integrity becomes paramount [9]. Interoperability poses its trials, with disparate software and platforms often at odds, hindering seamless integration [33]. Scalability demands attention, calling for solutions adapting to varying project magnitudes within PC operations. The technological intricacies of DT require specialized acumen, forming a barrier to entry for broader adaptation [33]. The initial financial outlay for DT implementation is substantial, which may deter smaller enterprises from embracing the technology [33]. Furthermore, the absence of standardization within the construction domain results in poor integration procedures and quality outcomes [11].

This research highlights certain gaps in the existing methodologies and practices concerning the assimilation of DT within the PC sector. Therefore, to foster a cohesive integration of DT in PC, a concerted effort towards standardization of data protocols is imperative to guarantee inter-system compatibility. A robust infrastructure for data management must be established, capable of safeguarding data integrity and facilitating real-time processing [9, 12]. Using sophisticated analytics and AI is essential to distill actionable insights from the collected data [12], enhancing predictive maintenance and decision-making. Moreover, high-speed and reliable connectivity is a prerequisite for effective communication across the DT ecosystem [9]. User interfaces must be intuitively designed to enable stakeholder engagement across varying levels of technical expertise [9]. Hence, educational initiatives are critical to equip the workforce with the necessary skills to navigate these advanced technologies. The convergence of DT with BIM is paramount, enriching the visualization and analytical facets of construction projects. DT solutions must be inherently scalable to accommodate a spectrum of project requirements. Additionally, compliance with regulatory standards and privacy legislation is essential. Consequently, investment in R&D is vital to drive innovation and refine DT applications tailored to the PC industry.

5 Conclusions and Limitations

This study presents the emergent route of DT integration within the PC sector, unraveling the methodological synergies and potential for industry-wide transformation. The research delineates the escalating adoption of DT, propelled by advancements in BIM, AI, and IoT, signifying a paradigm shift from traditional construction methods towards a digitized, efficient, and sustainable approach. Notably, the bibliometric analysis explains the focal research themes, geographical research proliferation, and the influential scholarly contributions shaping the DT-PC narrative. The content analysis accentuates its multifaceted objectives, from efficiency optimization to sustainability enhancement.

The article offers a conceptual framework outlining the integration of DT across PC stages, advocating for a seamless digital continuum from design to decommissioning. The findings highlight the pressing need for standardization, robust data management, and scalable solutions to navigate the complexities inherent in DT-PC integration. Notably, the study acknowledges the limitation of relying solely on the Scopus database. Future research can expand more emergent publications and should focus on empirical validation of DT models in PC, exploring advanced technologies for enhanced DT functionality, and developing interoperability standards. Investigating scalable solutions, data security, and environmental impacts, alongside economic analyses, will address critical gaps and advance the field significantly, paving the way for practical, scalable, and sustainable DT applications in PC.

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