Critical success factors for implementing digital twin technology in construction projects: A systematic and bibliometric approach

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Abstract

Digital twin (DT) technology is revolutionizing the construction industry by providing enhanced project oversight, predictive maintenance and optimized resource management via real-time data integration and virtual simulation. Despite its latent potential, successful DT implementation in construction projects requires an understanding of critical success factors (CSFs) that support effective deployment and integration. To achieve this, a bibliometric study was conducted after extracting 89 articles from the Scopus database. Subsequently, a qualitative systematic review was performed to synthesize extant literature and identify the CSFs, knowledge gaps and future research directions. Emergent findings indicate a growing number of published research articles on CSFs for DT implementation, underscoring exponential interest in the technology throughout the scientific community and industry. Moreover, significantly influential articles and the quintessential role of geographic collaboration were recognized. Finally, four knowledge gaps were emphasized; i) DT integration with emerging technologies; ii) lifecycle management and sustainability integration with DT; iii) human-centric factors and stakeholder collaboration for DT decision-making; and iv) policy and regulatory framework for DT implementation. This research serves as the first study employing a mixed-methods methodology and will provide scholars and practitioners with an extensive understanding of CSFs implementation in construction projects.

This research enhances digital innovation in the construction industry by implementing CSFs for DT adoption and offers actionable recommendations for industry practitioners who seek to augment their digital transition.

Keywords: digital twin; critical success factors; construction industry; bibliometric analysis; systematic review

1. Introduction

Construction industry activities typically accounts for approximately 7%–10% of the gross domestic product (GDP) in various countries, particularly in emerging nations (Bahamid et al., 2022). Because the industry is inextricably linked with other industries both upstream (i.e. delivering projects for clients) and downstream (i.e. purchasing raw materials and products from extractive and manufacturing sectors) of the supply chain, it generates vast employment opportunities and fosters wider socio-economic growth and development (Li et al., 2023). Despite its importance, numerous challenges doggedly persist on construction projects, including: lagging productivity, insufficient collaboration, sluggish technological progress, inadequate project outcomes and limited innovation (Zhang et al., 2024). These omnipresent challenges persist even though various advanced technologies designed to enhance productivity and performance are widely available to construction stakeholders (i.e. contractors, clients, engineers, architects and policy makers). Currently, the sector is undergoing a fundamental digital transformation, with emerging advanced technologies redefining project design, construction and management. For example, digital twin (DT) technology has sparked widespread interest due to its ability to create virtual replicas of actual assets, providing real-time data and insights throughout a project's lifecycle (Akanmu et al., 2021).

The origin of the DT concept was traced back to National Aeronautics and Space Administration (NASA), where a similar idea was used to create virtual models of spacecraft for simulation and monitoring purposes. However, at that time, the concept did not carry the formal name "Digital Twin." It was not until later that Michael Grieves introduced and formalized the term within the context of product lifecycle management. This reorganization of the narrative helps to clarify that although NASA employed the foundational principles of DT technology, the structured definition and naming were contributions that came afterward through academic refinement (Augustine, 2020). Digital models are simply a computer version of a physical system that has no interaction, whereas digital shadows are a one-way interaction between a digital duplicate and a physical object. Building information modelling (BIM), wireless networks of sensors, big data analytics and ML are all examples of enabling technologies that function in conjunction with DT (Boje et al., 2020). Data analytics, AI and neural networks enhance the capabilities of DT in anomaly detecting, optimising, estimating and in comprehending the overall condition of equipment or systems (Grieves, 2022).

Previous reviews of DT in construction depended on manual judgements premised upon a purely interpretivist philosophical approach adopted which could be biassed or subjective. For instance, (de Aguiar Corrêa et al. (2023) reviewed the digitization of the physical realm and its integration with the digital domain provide an opportunity to enhance the construction industry. Jiang et al. (2021) reviewed DT and its applications in the civil engineering sector; Bakhshi et al. (2024) identified DT applications for overcoming building supply chain challenges; and Shahzad et al. (2022) investigated the characteristics, applications and challenges related to DT in built environments. Collectively, these review papers evaluated the current state of DT in the construction industry and reiterate the growing popularity of the concept among both industry practitioners and scholars. However, none of these studies reviewed the critical success factors (CSFs) for implementing DT in construction projects.

Therefore, and against this contextual background, this paper adopts an exploratory sequential mixed methods design to investigate the CSFs for the effective deployment of DT in construction projects using a bibliometric analysis and systematic review. Three specific concomitant objectives are to: 1) identify annual publication trends regards CSFs for implementing DT in construction projects; 2) analyze influential journals, keywords and geospatial collaboration of research articles to establish clarity in the existing body of knowledge; and 3) determine knowledge gaps and future research directions for DT implementation. This review findings will assist academics in understanding the important components of implementing DT research and allow practitioners to prioritize CSFs that can improve information sharing and database administration in construction projects. Because stakeholders must understand the CSFs for DT implementation to make informed decisions, this review serves as a framework for allocating resources, identifying priorities and ensuring that DT implementation produce positive outcomes.

2. Background of digital twin in construction

DT represents a sophisticated digital breakthrough in the construction industry that resides in its early stages of adoption. This technology surpasses conventional BIM by enabling the digital duplicate to reflect the real entity throughout its lifespan. Construction activities are traditionally dependent on manual procedures and disjointed workflows which can significantly benefit from DT by providing enhanced design, construction and operating efficiencies (Jiang et al., 2021). DT is transforming the conceptualization, execution and management of construction projects. During the design phase, DT allow architects and engineers to evaluate structural designs and assess environmental performance via sophisticated simulations, thereby reducing errors prior to construction commencement (Ozturk, 2021). Throughout the construction phase, the incorporation of IoT devices and real-time data streams enables project managers to oversee progress, allocate resources and mitigate risks proactively. The integration of DT technology in construction offers a significant improvement over traditional techniques like time-lapse photography. While time-lapse visuals provide static, retrospective documentation of project progress, DT enables real-time data capture, analysis, and visualization throughout the lifecycle of a building. It facilitates continuous monitoring, predictive maintenance, and scenario simulation, which are not possible with passive methods like photography. Unlike time-lapse, DT is interactive and data-rich, offering a dynamic digital replica that evolves with the physical asset. This advancement enhances decision-making, risk mitigation, and project efficiency across all stages of construction and facility management (Yang et al., 2015). Following construction, DT enhances facility management by delivering insights into building and infrastructure performance, forecasting maintenance requirements and managing energy consumption (Jiang et al., 2022).

The advancement of DT in construction stems from the constraints of conventional methods and the urgent demand for innovation in an industry characterized by inefficiency and fragmentation (Rafsanjani and Nabizadeh, 2023). Traditionally, building projects depended significantly on paper-based plans, manual procedures, and static data models, frequently resulting in cost overruns, delays, and communication failures among stakeholders (Hasan et al., 2022). The introduction of BIM represented a substantial advancement by offering a digital framework for the creation, management, and dissemination of building information across a project's lifecycle. BIM concentrates on design and planning, but DT enhances functionality by incorporating real-time data and facilitating interaction with the physical asset. This dynamic capability enables project managers and operators to track progress, simulate scenarios, and enhance performance in previously unachievable ways (Lu et al., 2020).

Despite its inherent potential, DT in construction remains nascent and is accompanied by numerous barriers to adoption including significant expenses; technological intricacies; data security issues; and a deficiency of qualified personnel (Opoku et al., 2023). Surmounting these barriers necessitates a detailed comprehension of the technology's context, its advantages and the essential elements required for its effective execution. Several review studies undertaken have investigated the applicability of DT in the sector. For example, Opoku et al. (2022) sought to determine the drivers of DT; Wang et al. (2024) investigated the risks involved with its implementation; Xie et al. (2023) highlighted the knowledge map and forecasts of DT; and Zhang et al. (2024) examined DT's impact upon the sustainability of the sector. In other research, Boje et al. (2020) facilitated the development of the construction DT concept and Javaid et al. (2023) explored applications of DT in Industry 4.0. Table 1 contains a summary of review articles on DT in the construction industry. Despite research undertaken on DT in the construction industry, there is a notable lack of study on the implementation of CSFs in the sector. Moreover, review studies conducted used a purely qualitative methodology, which could lead to increased subjective and prejudice, undermining their validity.

Table 1. Summary of reviews on DT in the construction industry

S/N	Research Methodology	Research Theme	Timespan	Source
1.	Systematic literature review	Drivers of DT adoption in the construction industry	2018-2023	[16]
2.	Literature review	Risks of implementing DT in construction projects	2018-2023	[17]
3.	Scientometric analysis	Knowledge map and DT forecast	2011-2020	[18]
4.	Systematic literature review	Sustainability	2010–2023	[19]
5.	Systematic literature Review	Semantic construction DT	2020	[8]
6.	Literature review	Industry 4.0.	2023	[20]
7.	Systematic literature Review	Construction management	2023	[21]
8.	Systematic literature review	Decarbonization operating buildings	2018-2023	[22]
9.	Systematic literature review	Sustainability	2024	[23]
10.	Systematic literature review	DT applications in construction	2015-2022	[24]

11.	Literature review	Intelligent green building	2022	[25]
12.	Scientometric analysis	Architectural, engineering, construction, operation, and facility management (AECO-FM) industry	2023	[26]
13.	Systematic literature review	DT paradigm	2021	[27]

3. Research method

This review study used an exploratory sequential mixed methods design (Borrego et al., 2009), using a bibliometric analysis and systematic review to study the phenomenon under investigation (CSFs for DT implementation). The bibliometric component offers a quantitative mapping of the existing scholarly literature, focusing on publication trends, citation patterns, and co-authorship networks. This data helps to identify key contributors and the overall structure of the research landscape. Complementing this, the systematic review provides a synthesis of the literature to identify CSFs associated with DT implementation in construction. Consequently, the process is more precisely characterized as a dual-phased bibliographic and content analysis review.

3.1 Data Collection

Relevant articles were identified using a keyword search of the Scopus database, which contains a wider range of journals and more recent publications than other databases like Web of Science (Schotten et al., 2017). Moreover, Scopus has a superior indexing rate and broader coverage when compared to other academic databases (Meho and Yang, 2007). The search string included the following phrases: "digital twin*" OR "virtual counterpart*" OR "digital replica" OR "virtual twin*" OR "digital twin concept" AND "construction" AND "projects" AND "critical" OR "success" OR "factor" OR "impact" OR "influence" with no time constraints imposed. A total of 203 papers were initially identified and subject to two further rounds of manual screening. In the first round of screening papers were assessed based on particular criteria, such as engineering subject area, document type (article), publication status (final) and language (English). The search was conducted in October 2024. Conference papers were then excluded from consideration due to their content being deemed less valuable than peer reviewed journal publications. Subsequently, 110 papers were selected for continued analysis of their suitability to study. In the second round of screening, the abstracts of each paper were analyzed to determine which specific papers contained sufficient information on the phenomenon under investigation to be entered into final analysis.

Following this stage, twenty-one articles were eliminated and a total of 89 journal articles were eventually kept for the purpose of bibliometric analysis. Fig. 1. elaborates the overview of research methodology.

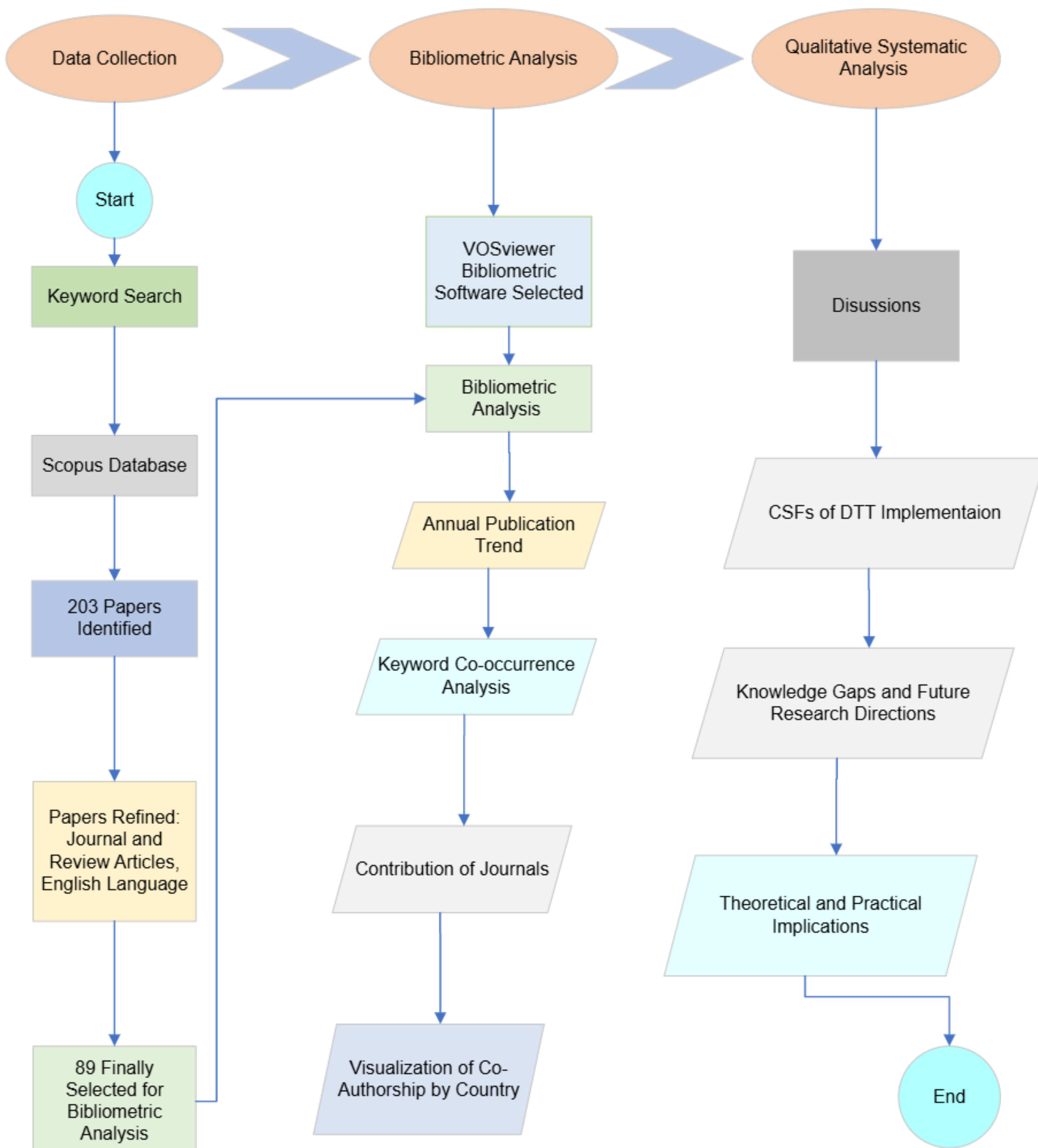

Fig. 1. Overview of research methodology

3.2 *Bibliometric analysis*

Bibliometric analysis is a technique that uses statistical tools to examine publications, citations and trends in academic literature. It is often used to assess the impact of research, identify trends and study relationships between diverse publications, authors, organizations and countries (Donthu et al., 2021). This approach provides objective, data-driven insights into the structure and dynamics of a study topic, allowing scholars to track the evolution and influence of academic output. There are numerous bibliometric analysis tools available (including Gephi, CiteSpace, Sci2, HistCite and VOSviewer) and each has its own set of skills and potentialities. VOSviewer was used for this study because it includes fundamental functions for developing, visualizing and analyzing bibliometric networks and is widely used in construction literature (Oladinrin et al., 2023). Furthermore, the outcomes of the document analysis, countries/regions co-occurrence analysis and keywords co-occurrence analysis are illustrated in the data visualization indexed in VOSviewer.

3.3 *Systematic analysis*

This study employed a systematic analysis that adheres to an organized and transparent review procedure to identify, analyze, and synthesize the CSFs for the implementation of DT technology in construction projects. Initially, a comprehensive literature search was performed using the academic database Scopus (Debrah et al., 2022). The inclusion criteria emphasized peer-reviewed journal articles published in English, whereas the exclusion criteria eliminated articles not in English, those addressing themes outside of engineering, and articles not centered on DT. Subsequent to the database search, titles and abstracts were evaluated for pertinence. Additionally, full-text articles were examined to verify eligibility according to predefined criteria (Zhang et al., 2022). A final set of high-quality articles formed the bibliographic portfolio used for analysis. This review, although not utilizing qualitative methodologies in the conventional manner, combines narrative interpretation of results with bibliometric analysis, including publication trends, countries/regions co-occurrence analysis and keywords co-occurrence analysis.

4. Analysis and results

Fig. 2. depicts the yearly distribution of the chosen articles. Prior to 2019, no articles had been published that discussed CSFs of DT in construction projects. It was found that in 2023, the maximum number of articles (frequency (*f*) = 32) had been published and in 2024 (as of October

2024) a further $f = 28$ articles were published. Further research publications in this field of DT in construction projects are anticipated because it represents a cornerstone of investigation for the sector's digital transformation. The growing number of articles produced year on-year substantiates this insight. The increase in publications beginning in 2019 align with the broader integration of DT and BIM technologies in the construction sector, suggesting that civil engineering and construction management began to embrace these innovations later than other industries, such as aerospace or manufacturing where the concept first emerged in the early 2000s. This delayed uptake may reflect the sector's traditionally conservative nature and slower digital transformation pace. Additionally, the apparent drop in publications in 2024 should not be interpreted as a decline in interest or output. The data collection for this review was conducted before the conclusion of the 2024 calendar year, and therefore does not include the full volume of that year's publications. As such, any dip in 2024 publication frequency is likely due to incomplete data and should be cautiously interpreted. These contextual factors are important when assessing publication trends and drawing conclusions from the bibliometric results.

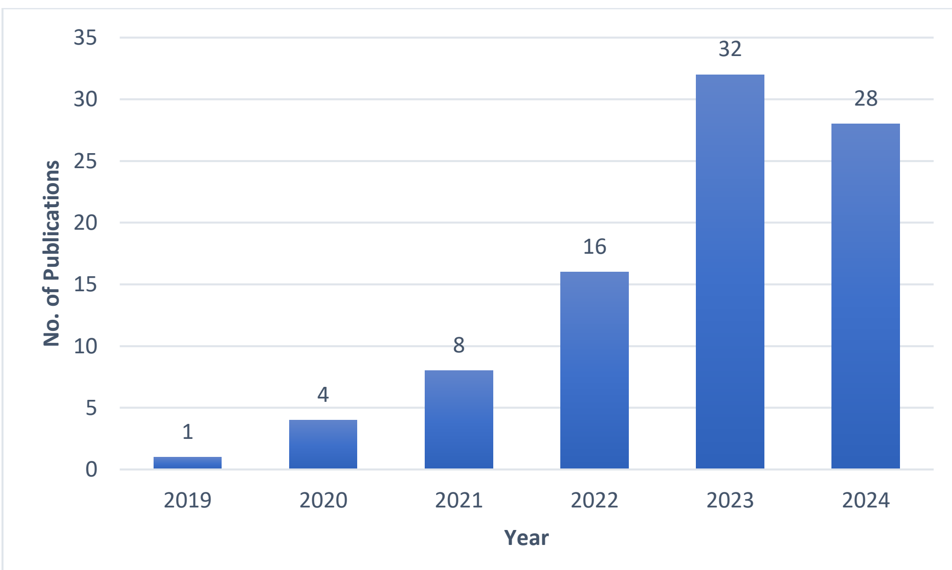

Fig. 2. Number of publications

4.1 Leading peer-reviewed journals analysis

Journal publication is essential for academics to disseminate their recent discoveries to a worldwide audience, resulting in enhanced knowledge and knowledge exchange (Hong et al., 2012). This enables scholars to remain updated on emerging theories, methods and findings. Journals provide a link between academic research and industry by disseminating novel theories, approaches and strategies for application. This could result in novel innovations, enhanced workflows and increased industry competitiveness hence, this analysis was conducted with this consideration in mind. It was determined that the journal Automation in Construction had the largest publication count, followed by Buildings, Applied Sciences (Switzerland), Smart and Sustainable Built Environment and Sensors. These journals reside at the cutting edge of digital knowledge within construction research therefore, justifying their prominence in the field (refer to Table 2).

Table 2. Contribution of journals

Source Title	Number of Studies	Publication Per Year
Automation in Construction	15	2020-2022
Buildings	14	2023-2024
Applied Sciences (Switzerland)	8	2023
Smart and Sustainable Built Environment	6	2022
Sensors	5	2021

4.2 Keywords co-occurrence analysis

Keyword co-occurrence analysis is an effective bibliometric technique for elucidating connections between concepts by assessing the frequency with which specific keywords co-appear in scholarly articles (Nazir et al., 2021). This technique facilitates the identification of thematic patterns, the development of trends, and the conceptual framework within a study domain. The utilization of 'author keywords' in VOSviewer (with a 'minimum number of occurrences' set to 3), resulted in a preliminary selection of 32 from a total of 382 author keywords. The strengths of connections among network nodes can be assessed by examining the thickness of the edges, which signify the interactions between keywords. Fig. 3. illustrates a distinct correlation between node widths and the frequency of term occurrence in the literature; where the closeness of the nodes indicates a strong association between them.

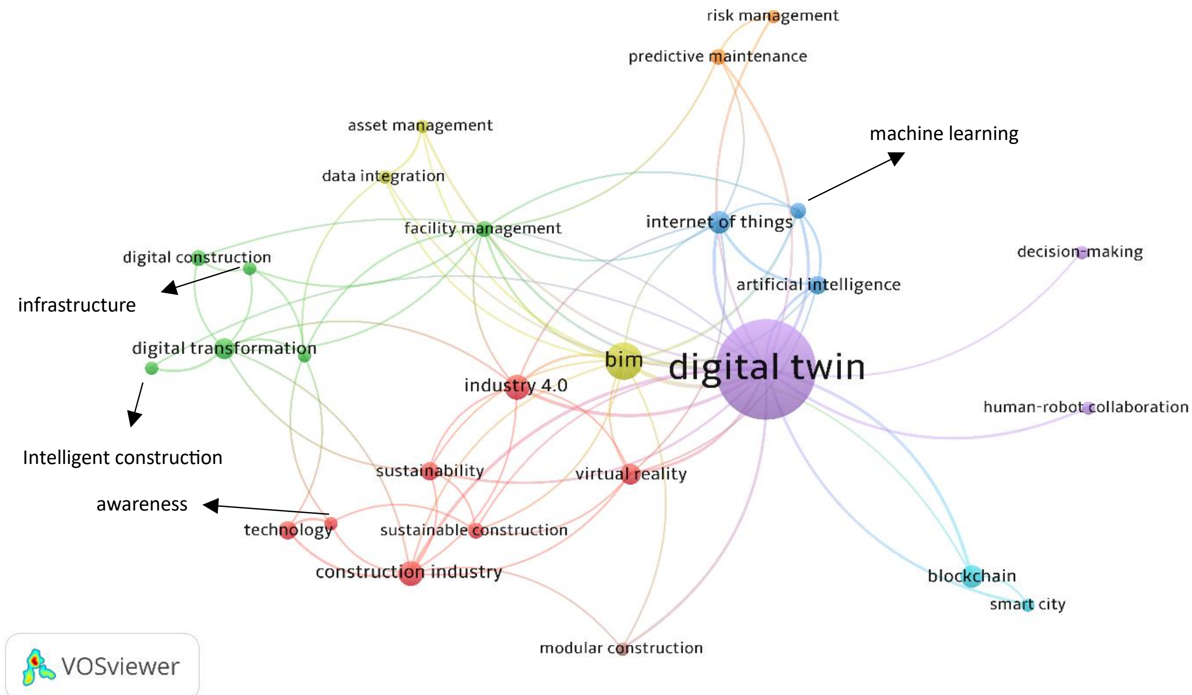

Fig. 3. Keywords co-occurrence analysis

The most commonly examined keywords encompass “digital twin,” “BIM,” “digital construction” and “blockchain.” This analysis of keyword co-occurrence enables institutions and researchers to leverage such data to inform future research directions, facilitating alignment with emerging trends and underexplored challenges that hold innovation potential. However, the findings are somewhat unsurprising given that three of the prominent terms were search terms and so this result was somewhat *fait accompli*. The inclusion of “blockchain” was not anticipated and underscores elevated industry and academic concerns regards the security of digital data. Such data has a corporate value and can be exploited by nefarious actors (so called black hatters) for commercial gain (Parn and Edwards, 2019). Table 3 presents a quantitative summary of the co-occurrence analysis of keywords related to CSFs for the implementation of DT in construction projects.

Table 3. Quantitative summary of co-occurrence analysis of keywords

Keyword	Occurrence	Total Link Strength
Digital Twin	70	102
BIM	45	85
Digital Construction	32	84
Blockchain	28	80
Construction Industry	21	78
Facility Management	18	72
Human-Robot Collaboration	15	68
Industry 4.0	12	63
Infrastructure	10	60
Intelligent Construction	08	55
Internet of Things	07	52
Machine Learning	06	49
Modular Construction	06	46
Risk Management	06	43
Smart City	06	38
Sustainability	05	33
Sustainable Construction	05	30
Technology	05	27
Virtual Reality	04	25
Decision-Making	04	22
Data Integration	04	20
Artificial Intelligence	03	18
Construction	02	17
Asset Management	02	15
Awareness	02	12
Digital Transformation	02	11

The total link strength in this context refers to the cumulative strength of all links a keyword has with other keywords in the bibliometric network. In co-occurrence analysis, a link is established between two keywords when they appear together in the same publication. The more frequently two keywords co-occur in different documents, the stronger the link between them, and the higher their link strength.

In current study total link strength is calculated by VOSviewer based on the number of co-occurrences between a keyword and all other keywords in the dataset. For example:

- "Digital Twin" has the highest occurrence (70) and the highest total link strength (102). This suggests that "Digital Twin" is not only frequently mentioned but is also strongly connected to many other terms, such as "BIM," "IoT," and "Industry 4.0."
- "Blockchain", with 28 occurrences and Total Link Strength of 80, shows that while it appears less frequently than "Digital Twin" or "BIM," it has strong relational ties to a wide set of keywords, indicating its growing importance in digital construction discourse.

4.3 Geospatial collaboration of research articles

VOSviewer maps geospatial collaborations to identify which countries are actively collaborating on research, the strength of these connections and the global network of scientific partnerships. Such analysis is invaluable for comprehending worldwide research dynamics and the roles of various countries in promoting specific fields of study. Fig. 4. illustrates the geospatial distribution of the chosen articles. It elucidates upon global research networks, highlights the predominance of specific locations in the field and illustrates the level of international collaboration influencing advancements in the subject. China, the United Kingdom and Italy are geographically proximate. The bigger node or occurrence indicates that China occupies the dominant position. The dimensions of a node reflect its frequency or influence within the network, signifying that China holds a more significant position in the domain of DT research publications. Conversely, smaller nodes like Singapore and South Korea may lack comparable exposure or influence; yet, they can still signify important, contributing to research articles in the domain of DT. The geospatial collaboration analysis conducted in this study is based primarily on the institutional affiliations of the contributing authors, as indexed in the Scopus database. It is important to clarify that these affiliations do not necessarily correspond to the geographical locations where the research was conducted or where DT technology was implemented in construction projects. The high volume of publications from these countries reflects their academic infrastructure, investment in research, and scholarly interest in DT technology rather than a direct correlation with implementation on the ground.

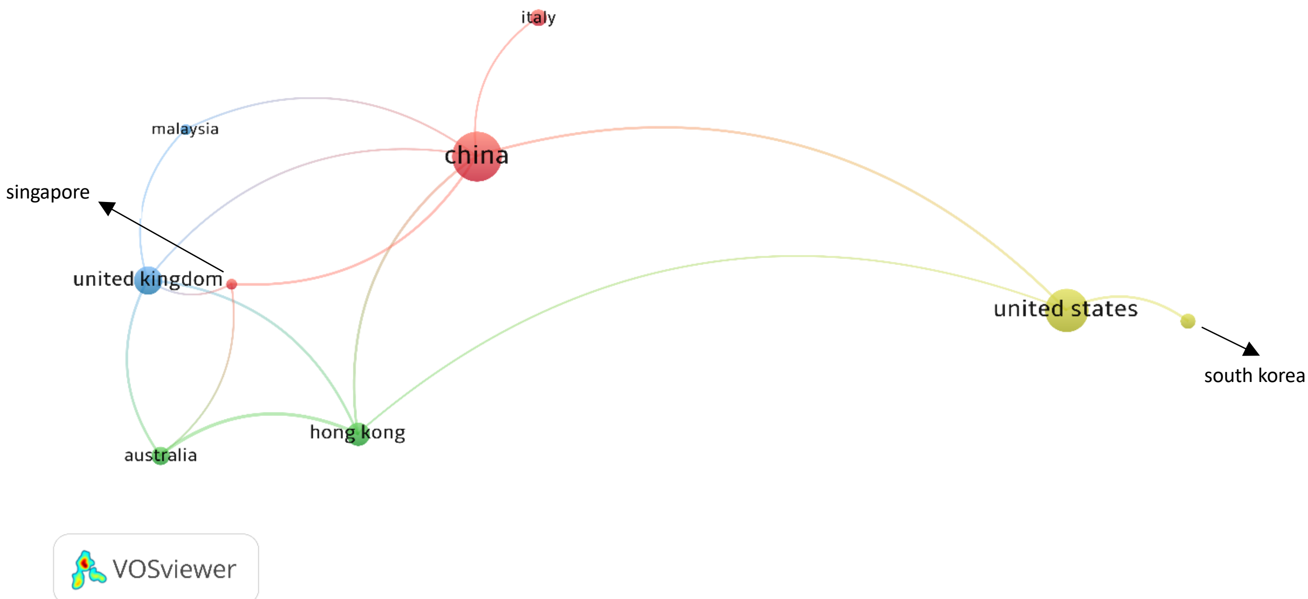

Fig. 4. Visualization of co-authorship by country

Table 4 provides a geospatial collaboration analysis of the contributions of countries to CSFs for DT in the construction projects. China has been identified as the primary contributor, maintaining robust relationships with other nations with 562 citations, while Hong Kong follows with 230 citations. The average publication year for the countries in this research field is 2023 for Hong Kong, Italy, and the United Kingdom, while China and the United States have an average publication year of 2024. The United Kingdom obtained the greatest average normalized citations value (1.90), signifying that its outcomes exerted the most significant impact on the implementation of CSFs for DT in construction research. The prominence of developed nations as producers of new literature perhaps indicates the growing knowledge gap with the developing world who lag behind technology adoption. Such a trend does not bode well for their socio-economic development and perhaps more work is needed in developing nations to understand why.

Table 4. Quantitative analysis of co-authorship analysis by country

Country	Citations	Average Publication Year	Average Citations	Average Normalized Citations
China	562	2024	18.8	1.16
Hong Kong	230	2023	19.2	1.27
Italy	86	2023	10.7	0.63
Malaysia	12	2022	2.40	0.75
Singapore	63	2022	12.6	0.44
South Korea	58	2022	8.25	1.20
United Kingdom	161	2023	17.4	1.90
United States	141	2024	25.5	1.12

5. Discussion

CSFs are vital aspects or conditions necessary for effective project execution, especially in intricate and dynamic settings such as the construction industry (Ali et al., 2024). Recognizing and addressing these CSFs can markedly enhance project results, increase stakeholder satisfaction and guarantee the prompt, economical completion of construction projects. In addition, CSFs for DT can be delineated as a collection of vital characteristics and domains that facilitate swift advancement in the industry. To successfully implement DT in construction projects, academics and practitioners must identify the CSFs to facilitate effective execution in these essential domains. Table 5 presents a summary of CSFs of DT implementation in construction projects. These CSFs refer to domains or procedures within a construction project that enable renewal, information distribution, evolution and database management. These 20 terms were selected based on a systematic review and bibliometric analysis of existing literature in the context of DT technology in construction. The analysis highlighted the critical role of 20 CSFs for the successful implementation of DT in construction projects. The following sections will delve into the top 5 key CSFs in detail. To clarify, each of the CSFs presented in Table 5 was identified through a synthesis of various sources that discussed success factors for the adoption and implementation of DT technology. We did not extract these factors from a single study but instead integrated the findings from multiple sources, where these terms were either explicitly listed or implied as essential for DT technology in construction projects.

Table 5. Overview of relevant papers regarding CSFs for the implementation of DT in the construction projects.

Item	Critical Success Factors	Total	Rank	Source
1	Enhancing energy efficiency	35	1	(Maddaloni and Sabini, 2022), (Koltsios et al., 2022), (Banfi et al., 2022), (Tan et al., 2022), (Clausen et al., 2021),(Bortolini et al., 2022), (Agostinelli et al., 2021), (Tahmasebinia et al., 2023), (Arowoiya et al., 2024), (Do Amaral et al., 2023), (Francisco et al., 2020), (Cespedes-Cubides and Jradi, 2024), (Fathy et al., 2021), (Ghenai et al., 2022), (Teng et al., 2021), (Spudys et al., 2023), (Kaewunruen et al., 2019), (Zaballos et al., 2020), (Huang et al., 2022), (Semeraro et al., 2023), (Yeom et al., 2024), (Tagliabue et al., 2021), (Onile et al., 2021), (Piras et al., 2024a), (Jiang et al., 2022a), (Qian et al., 2024), (ElArwady et al., 2024), (Demianenko and De Gaetani, 2021), (Lydon et al., 2019), (Asif et al., 2024), (Sharma and Gupta, 2024), (Liu et al., 2020), (Figueiredo et al., 2024), (Kineber et al., 2023), (Chen et al., 2021)
2	Technology integration (BIM)	27	2	(Figueiredo et al., 2024), (Daniotti et al., 2022), (Nguyen and Adhikari, 2023), (Onile et al., 2021), (Alnaser et al., 2024), (Radzi et al., 2024), (Sepasgozar et al., 2023), (Boje et al., 2023), (Tahmasebinia et al., 2023), (Rashidi et al., 2024), (Asif et al., 2024), (Spudys et al., 2023), (Jiang et al., 2022a), (Xie et al., 2023), (Qian et al., 2024), (Piras et al., 2024b), (Huang et al., 2022), (W. Wang et al., 2022), (Bortolini et al., 2022), (Do Amaral et al., 2023), (Sun and Liu, 2022), (Liu et al., 2020), (W. Wang et al., 2024), (Koltsios et al., 2022), (Alizadehsalehi and Yitmen, 2023), (Banfi et al., 2022), (T. Wang et al., 2022)
3	Top management support	20	3	(Jiang et al., 2024), (Attar et al., 2024), (Oke et al., n.d.), (Bello et al., 2024), (Adetunji et al., 2024), (Errandonea et al., 2020), (Agnusdei et al., 2021), (Roohollah et al., 2024), (Spudys et al., 2023), (Hu et al., 2022), (ElArwady et al., 2024), (Zhao et al., 2022), (Shi et al., 2023), (Shahat et al., 2021), (Meng et al., 2023), (Afzal et al., 2023), (Kaewunruen et al., 2019), (Zaballos et al., 2020), (Vuoto et al., 2023), (Mahmoodian et al., 2022)

4	Data availability	13	4	(Kang and Mo, 2024), (Adetunji et al., 2024), (Errandonea et al., 2020), (Agnusdei et al., 2021), (Madni et al., 2019), (Hakiri et al., 2024), (Iqbal et al., 2024), (Botín-Sanabria et al., 2022), (Hu et al., 2022), (Zhao et al., 2022), (Jeong et al., 2024), (Vuoto et al., 2023), (Mahmoodian et al., 2022)
5	Stakeholder engagement and collaboration	11	5	(Daniotti et al., 2022), (Sassanelli et al., 2024), (Kineber et al., 2023), (Piras et al., 2024b), (Teisserenc and Sepasgozar, 2022), (Lee et al., 2021), (Torres et al., 2024), (Alizadehsalehi and Yitmen, 2023), (Opoku et al., 2023), (Desogus et al., 2023), (Kober et al., 2024)
6	Cybersecurity and data privacy	07	6	(Stergiou et al., 2023), (Hu et al., 2022), (Salim et al., 2022), (Alnaser et al., 2024), (Radzi et al., 2024), (Jiang et al., 2022b), (Saif et al., 2024)
7	Enhance supply chain management	07	6	(Bhandal et al., 2022), (Nguyen et al., 2022), (Stadtfeld et al., n.d.), (Guo and Mantravadi, n.d.), (Lee and Lee, 2021), (Abideen et al., 2021), (Ivanov and Dolgui, 2021)
8	Cost management	05	8	(Banfi et al., 2022), (Li et al., 2024), (Augustine, 2020), (West et al., 2021), (Lo et al., 2021)
9	Mitigating conflicts and hazards	04	9	(Desogus et al., 2023), (M. Wang et al., 2024), (Ariyachandra and Wedawatta, 2023), (Cheng et al., 2023)
10	Regulatory compliance	03	10	(Fakhraian et al., 2023), (Mêda et al., 2021), (Kosse et al., 2022)
11	Client commitment	03	10	(Daniotti et al., 2022), (Errandonea et al., 2020), (Mahmoodian et al., 2022)
12	Regular performance evaluation	03	10	(Iqbal et al., 2024), (Botín-Sanabria et al., 2022), (Hu et al., 2022)
13	Contractual agreements	03	10	(Roohollah et al., 2024), (Spudys et al., 2023), (Hu et al., 2022)
14	Skilled workers and technical supervisors	03	10	(Do Amaral et al., 2023), (Sun and Liu, 2022), (Liu et al., 2020)
15	Contractor leadership and assistance	02	15	(Shahat et al., 2021), (Meng et al., 2023)
16	Change management and organisational culture	02	15	(Broo and Schooling, 2023), (Vieira et al., 2023)

17	Promoting skilled workforce and training	02	15	(Hazrat et al., 2023), (Beda et al., 2023)
18	Constantly gaining knowledge and expertise	02	15	(Oke et al., 2023), (Bello et al., 2024)
19	Avoiding owner delays	01	19	(Mahmoodian et al., 2022)
20	Appropriate site arrangement	01	19	(Kober et al., 2024)

5.1. Enhancing energy efficiency

Effective and successful implementation of DT in construction projects has the latent potential to engender high energy efficiency to obtain sustainable building operations (Vrchota et al., 2020). This entails optimizing the design, construction and operational phases of buildings to minimize energy use for heating, cooling, lighting and other systems. Several studies underscore the value of DT for enhancing energy efficiency particularly when used in conjunction with other advanced digital technologies (Agostinelli et al., 2021), for example: Deng et al. (2022) used a digital identity to analyze indoor thermal comfort for human-centered monitoring in smart buildings; Hosamo et al. (2023) employed an artificial neural network alongside a multi-objective genetic algorithm to enhance thermal comfort and reduce energy consumption, achieving energy savings of 10.8% to 13.2% during the summer months; and Peng et al. (2020) planned to cut the amount of energy that was consumed by a hospital in China by 1% with a DT control center.

Song et al. (2023) proffers that DT serves as the foundation for a data-model fusion dispatch method for improving building energy adaptability. Through constant surveillance of energy consumption, DT can guarantee that buildings adhere to energy rules during their operational lifespan and help directly reduce a building's carbon emissions and minimizing environmental impact. Enhancing energy efficiency with DT presents significant opportunities for the building sector because it utilizes real-time data, predictive analytics and sophisticated simulations to enhance building design, operations and maintenance, hence minimizing energy consumption (Chen et al., 2021). Enhanced energy efficiency yields financial savings, superior building performance, adherence to regulations and environmental sustainability (Banfi et al., 2022). Although challenges such as substantial initial expenses and data administration require attention, the enduring benefits of energy-efficient buildings render DT an indispensable asset for the future of construction and building management.

5.2 Technology integration (BIM)

DT integration with current advanced digital technologies (including as BIM, IoT, cloud computing and project management tools), is essential for establishing a cohesive DT ecosystem. For example, integrating BIM with DT enables construction professionals to visualize, simulate, and manage projects with enhanced efficiency (Torres et al., 2024). BIM offers a digital depiction of the physical and functional attributes of construction projects. When combined with DT, BIM transforms from a static representation of the design phase into a dynamic, real-time instrument that reflects the actual progress and performance of the construction projects (Radzi et al., 2024). BIM integration enables the DT to transcend static design models by integrating real-time data from the construction sites. This data encompasses ambient variables (e.g. temperature, humidity), equipment utilization, material tracking and project advancement thus, facilitating ongoing monitoring (Wang et al., 2022). By integrating BIM with real-time data, DT can model various scenarios including the influence of weather on construction timelines and the repercussions of design modifications on construction efficacy. This assists project teams in enhancing decision-making and alleviating risks prior to their manifestation on-site (Jiang, 2021). Furthermore, BIM establishes the structural basis for a project, whereas the DT incorporates real-time analytics and data insights. Collectively, BIM and DT offer robust instruments for facilitating informed judgements concerning expenses, timelines and resource distribution (Aktürk and Irlayıcı Çakmak, 2024). Project managers can utilize real-time data to modify construction schedules or anticipate supply shortages. Successful integration of BIM and DT necessitates that construction industry personnel possess proficiency in both BIM software and DT platforms. However, the sector is experiencing a skills gap, as numerous construction personnel remain inadequately trained in these modern technologies.

5.3 Top management support

Support from top management is essential for the effective implementation of DT because it furnishes the strategic vision, resources and authority necessary to propel project advancement and organizational adoption (Vrchota et al., 2020). When senior management actively supports the DT endeavor, it creates a definitive organizational commitment that inspires teams at all levels to participate in and prioritize the project (Barham et al., 2020). This support frequently manifests as the provision of requisite cash, technological resources and manpower, which are crucial for tackling the intricacies of DT development (Cichosz et al., 2020). Furthermore, senior management can affect the incorporation of the DT into overarching organizational objectives, guaranteeing that its advancement corresponds with essential business aims and improves decision-making processes. In addition to supplying resources, the active participation of top management strengthens a culture of collaboration and ongoing enhancement, which is crucial for the sustained success of the DT. Management support help fosters interdepartmental collaboration, enhancing data exchange, dismantling barriers and motivating departments to offer distinct views to augment the DT (Meng et al., 2023). Consistent involvement from senior management guarantees that the project retains visibility and momentum throughout the company, aiding in the mitigation of resistance to change and cultivating an atmosphere conducive to the adoption of innovative technologies. By consistently highlighting the strategic significance of the DT, senior management can foster trust and galvanize a unified dedication to its effective execution and sustained utilization (Zhao et al., 2023).

5.4 Ensuring data availability

Data availability is a key success factor for the implementation and efficacy of DT. to replicate physical conditions and behaviors instantaneously (Piras et al., 2024). In the construction industry, project managers, architects, engineers and other stakeholders can depend on DT for immediate decision-making, risk management and performance evaluation (Botín-Sanabria et al., 2022). Inadequate, tardy or erroneous data input into the DT may result in poor decision-making based on its output, thereby causing delays, budget overruns or safety hazards. In addition, DT frequently aggregate data from diverse sources, including BIM systems, IoT devices (such as sensors monitoring ambient conditions), drones and previous project data (Yang et al., 2024). For the DT to function effectively, data from all these sources must be merged effortlessly and consistently.

5.5 Stakeholder engagement and collaboration

Key stakeholder engagement during the project is a crucial success factor in DT implementation because it promotes alignment, collaboration and responsiveness to real-world requirements.

Timely and continuous engagement from project owners, design teams, operators, end-users and regulatory bodies guarantees that the DT is created with a comprehensive grasp of objectives, user requirements and compliance standards (Ozturk, 2021). Furthermore, engaging stakeholders from the outset fosters a collective vision, diminishes resistance to implementation and guarantees that the DT's capabilities are tightly aligned with both operational and strategic objectives (Lehtinen and Aaltonen, 2020). Each stakeholder group contributes distinct viewpoints and knowledge, facilitating the development of a comprehensive and pragmatic digital twin that accurately represents the project's intricacies and addresses possible difficulties proactively (Lee et al., 2021). Ensuring continuous stakeholder engagement during the project necessitates efficient communication routes, feedback systems and well-defined roles (Mohsen Alawag et al., 2023). Consistent progress evaluations, collaborative platforms and organized feedback mechanisms enable stakeholders to offer ongoing input, guaranteeing that the DT adjusts to changing requirements and retains its relevance (Opoku et al., 2023). Furthermore, conducting training and knowledge-sharing sessions augments stakeholders' comprehension and confidence in the DT, hence, enhancing their capacity to utilize its insights and functions proficiently (Desogus et al., 2023). By addressing the distinct goals and priorities of each stakeholder, the project team develops a solution that delivers measurable value, promotes cross-functional collaboration, and ultimately enhances the project's success and sustainability. For example, Granacher et al. (2022) introduced a DT for decision-making in energy system design to overcome decision paralysis by providing improvements in sequential communication. Specifically, the decision maker could utilize visual aids to maintain transparent and adaptable dialogue throughout the solution development and exploration process.

6. Knowledge gaps & future research directions

Understanding CSFs for the implementation of DT in construction projects is becoming imperative as the industry undergoes a rapid digital transformation to improve project outcomes, operational efficiency and sustainability. Yet, despite the widely recognized promise of DT for better project management, predictive maintenance and real-time monitoring, there doggedly remain knowledge gaps that must be filled. Future studies in this field may have a substantial impact on the advancement of digital transformation in construction by addressing knowledge gaps and stressing practical solutions. Fig. 5. demonstrates the summary of knowledge gaps and future research directions.

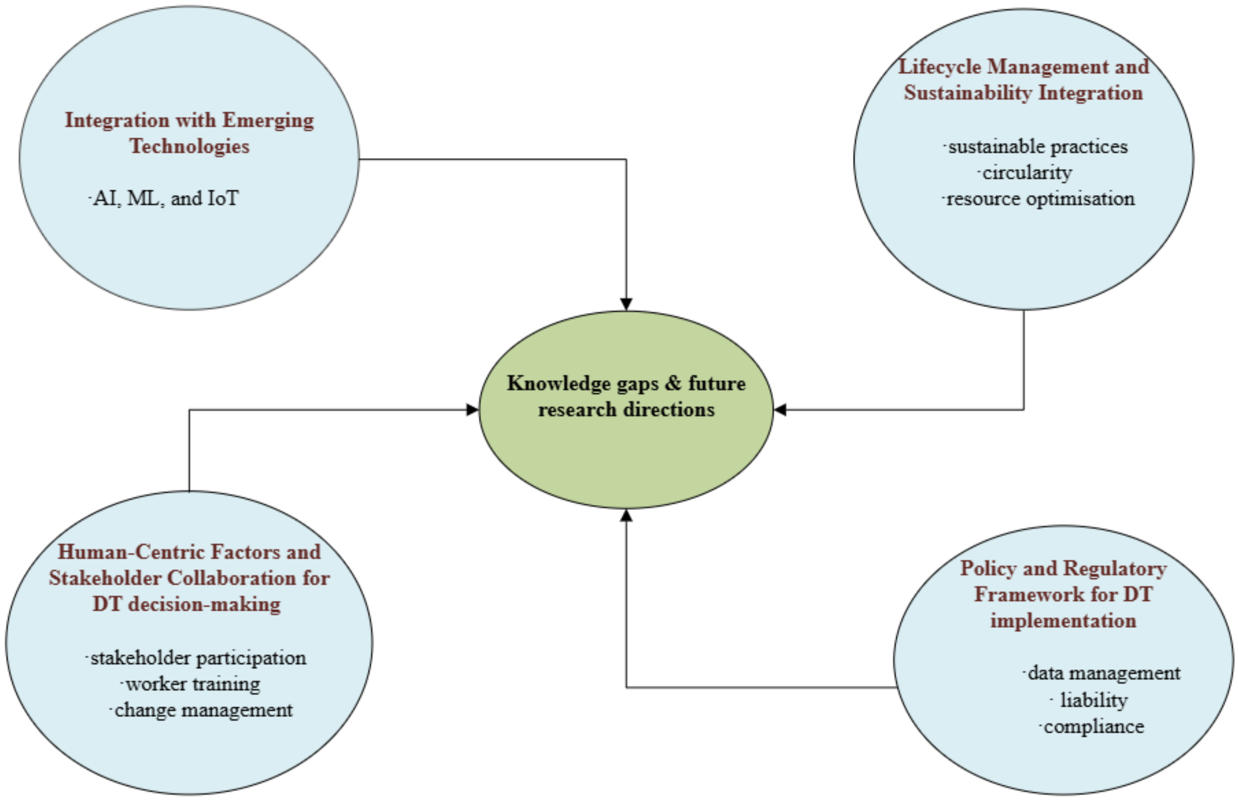

Fig.5 Summary of knowledge gaps and future research directions

6.1 Integration with Emerging Technologies

Although DT have great potential for enhancing project management, quality control and efficiency, their integration with other emerging technologies such as AI, ML and IoT remains scant. A limited number of empirical studies offer insight into how these technologies work together to improve the efficacy of DT in construction, particularly for real-time decision making (Opoku et al., 2021). One possibility is the high cost and technical complexity associated with implementing DT technology, which may make it less accessible to smaller firms or in regions with limited technological infrastructure. The advanced software, sensors, and computing power required for effective DT implementation are prohibitively expensive, especially in the early stages of adoption (Botín-Sanabria et al., 2022). Additionally, there is knowledge gap or lack of expertise in the construction sector regarding the integration of such technologies into construction projects. Furthermore, while interest in DT is growing, it is still an emerging field, and the application of such technologies in construction may not yet be widespread enough to generate a large volume of academic research (Singh et al., 2022). Therefore, the limited number of studies could reflect both technological barriers and the novelty of the field. Analyzing these synergies may provide strategies to utilize data-driven insights, enhance operations and optimize resource allocation. Furthermore, exploring the capabilities of predictive analytics in DT for proactive risk management may provide novel insights for improving construction safety (Botín-Sanabria et al., 2022). Moreover, DT functions as the integration center when IoT-acquired data, AI-generated insights and ML forecasts merge. It offers stakeholders an extensive, real-time perspective of assets and operations, enabling them to monitor and manage physical systems remotely. The integration of AI, ML and IoT renders DT exceptionally versatile and scalable across several sectors, ranging from minor applications such as building management to extensive smart city projects (Kor et al., 2023).

6.2 Lifecycle Management and Sustainability Integration

Although the introduction of DT has demonstrated efficacy in construction, their application for lifecycle management in the construction industry remains insufficiently investigated. Research on how DT may enhance sustainable practices, resource optimisation and circularity throughout a building's lifecycle is limited. Examining the integration of DT with lifetime assessment and sustainability measures would address this deficiency (Figueiredo et al., 2024). Research may concentrate on evaluating DT's function in monitoring building performance, energy efficiency and resource utilisation over time hence, aiding sustainability initiatives and fostering circularity in the construction industry. In addition, DT facilitates the modelling of environmentally friendly behaviours and the monitoring of real-time environmental parameters, fostering a proactive strategy for sustainability. The outcome is diminished greenhouse gas emissions, decreased waste and a reduced environmental footprint throughout the asset lifecycle (Kineber et al., 2023). Furthermore, the integration of DT with lifetime management and sustainability principles provides significant advantages for asset optimisation, resource efficiency and environmental stewardship. DT facilitate organisations in reducing environmental impact, prolonging asset lifespan and advancing circular economy objectives through real-time information and predictive capabilities. Despite challenges like data security and significant initial costs, the long-term advantages of DT in facilitating sustainable lifecycle management are considerable, rendering this integration crucial for industries aiming to comply with global sustainability goals and minimise their ecological impact (Chen et al., 2021).

6. 3 Human-Centric Factors and Stakeholder Collaboration

The significance of the human factor in the successful implementation of DT is often overlooked (Modoni and Sacco, 2023). Yet, there is limited research on the role of stakeholder participation, worker training and change management in the implementation of DT. Furthermore, there is a paucity of investigation about the influence of DT on project roles, workflows and decision-making processes (Zhang et al., 2023). Subsequent research may explore optimal methods for workforce training and stakeholder collaboration, guaranteeing that teams are equipped and inclined to embrace DT. Additionally, understanding the social and cultural factors that influence DT acceptance can help in designing user-centric DT solutions that meet the needs of diverse stakeholders within the construction industry (Kober et al., 2024).

6.4 Policy and Regulatory Framework

The construction industry lacks defined legal frameworks and rules for DT; albeit the new European Regulations for AI are an attempt to address this deficiency (Agostinelli et al., 2021). Research regarding the influence of regulations on DT implementation and the integration of DT within current legal frameworks is scarce, resulting in uncertainties for stakeholders. Researchers ought to investigate the influence of policy on DT implementation, especially around data management, liability and compliance. Examining legislative incentives or regulatory frameworks that could promote DT implementation may enhance confidence and conformity with industry norms, facilitating widespread implementation (Omrany et al., 2024). While policies and regulations are designed primarily to ensure safety, accountability, data protection, and interoperability especially critical in the context of complex digital systems like DT, they can also unintentionally impede innovation. Regulations provide a structured foundation that promotes trust, standardization, and ethical practices, which are essential for the broad adoption of emerging technologies (Hosamo et al., 2022). However, overly rigid or outdated regulatory frameworks can stifle experimentation and slow the pace of technological advancement. In the case of DT in construction, a balanced regulatory approach is essential: one that protects public and environmental interests while remaining adaptive to rapid technological changes. Therefore, the main reason for regulations is to create a safe and equitable technological ecosystem, but they must evolve in tandem with innovation to remain truly beneficial (Su et al., 2023).

7. Conclusion

To fully realise the potential of DT, it is essential to address the CSFs that facilitate its effective implementation. The research objectives of this study were successfully achieved and it was found that growing trend of publication articles on DT implementation in the construction projects has been shown to boost its applied relevancy. Furthermore, it was revealed that China has become the leading contributor to research on DT implementation. This study has identified CSFs, namely: i) enhancing energy efficiency, ii) technology integration (BIM), iii) top management support, iv) ensuring data availability and v) enhancing stakeholder engagement and collaboration, all of which are vital for cultivating a conducive environment for DT in the construction projects. The effective implementation of DT in construction projects relies on a comprehensive strategy that addresses both technological and human elements. By addressing these CSFs, industry stakeholders may realize the comprehensive advantages of DT, resulting in enhanced project outcomes, diminished environmental impact and sustained asset value.

This review study will motivate researchers to investigate more profound applications of DT. DT establishes a novel theoretical framework for real-time data integration, thereby contesting conventional static models in building project management. Novel theoretical perspectives presented on real-time decision-making, predictive analysis and ongoing project optimization, offers the potential to enhance adaptive project management theories and support innovative approaches for managing complex projects. Emergent findings serve as the first comprehensive review of the body of knowledge for the effective implementation of DT in the construction projects. For practical implications, this study provides practitioners in the construction projects with a concise and easily accessible synthesis of the latest research on CSFs implementation in construction industry. Moreover, DT diminishes misunderstandings and enhances collaboration, hence reducing the likelihood of rework and fostering more accountability. This results in expedited decision-making, enhanced project transparency, and a decrease in project delays, hence increasing project success rates. With high reputational stakes and low profits margins on construction projects, technologies that enable to gain a competitive advantage will ultimately become established within practice and push higher performance forward in a Darwinian manner. Such palpable benefits cannot be overlooked by practitioners and those who do will invariably become uncompetitive and insolvent. The limitation of this study is that the search was conducted in October 2024. It is important to acknowledge a limitation inherent to the nature of academic publication. Emerging and technology-driven topics often experience longer peer-review and publication cycles, which may result in a lag between research execution and its appearance in indexed journals. Consequently, some of the most recent or cutting-edge advancements may not yet be reflected in the analyzed dataset, potentially influencing the comprehensiveness of the findings.

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