A scientometric analysis and critical review of digital twin applications in project operation and maintenance

Abstract

Purpose – Recent emerging information technologies like digital twin (DT) provide new concepts and transform information management processes in the architecture, engineering, and construction (AEC) industries. Although numerous articles are pertinent to DT applications, existing research areas and potential directions related to the state-of-the-art DT in project operation and maintenance (O&M) are yet to be studied. Therefore, this paper aims to review the state-of-the-art research on DT applications in project O&M.

Design/methodology/approach – To do this, the current review adopted four methodological steps, including literature search, literature selection, science mapping analysis, and qualitative discussion to gain a deeper understanding of DT in project O&M. The impact and contribution of keywords and documents were examined from a total of 444 journal articles retrieved from the Scopus database.

Findings – Five mainstream research topics were identified, including (1) DT-based artificial intelligence (AI) technology for project O&M, (2) DT-enabled smart city and sustainability, (3) DT applications for project asset management, (4) Blockchain-integrated DT for project O&M, and (5) DT for advanced project management. Subsequently, research gaps and future research directions were proposed.

Originality – This study intends to raise awareness of future research by summarising the current DT development phases and their impact on DT implementation in project O&M among researchers and practitioners.

Keywords: Digital twin; Information technologies; Project operation and maintenance; Scientometric; Construction industry

Paper type: Literature review

1. Introduction

Data has become one of the most valuable assets in the world today; the data from engineering assets and systems are essential for equipment monitoring and diagnostics (Shi et al., 2023). The use of data also significantly influences decision-making across the project management life cycle because the capability and quality of project performance have increased due to enterprises using descriptive project data analytics (Kaewunruen and Lian, 2019). The development of simulation and data-relevant technologies is growing within the Fourth Industrial Revolution (4IR). Deloitte Insight (2021) suggested that over 70% of respondents to the investigation expressed that their organisations are utilising or exploiting artificial intelligence (AI). Analytics and cognition will have the second-largest demonstrable influence on enterprises in the next three years, according to more than 90% of chief information officers (CIOs) and senior technology directors (Deloitte Insight, 2020). Therefore, the construction industry has focused primarily on smart project asset management under the 4IR era.

Project operation and maintenance (O&M) typically lasted more than 50 years, making it difficult to challenge smart construction management (Wang et al., 2023). Each project's construction costs include a sizeable portion of the O&M phase. Data information is essential for building daily management and entity equipment such as cameras. One of the biggest challenges in the process of O&M management is maintaining the integrity, validity, and interactional of data (Wetzel and Thabet, 2015). The evidence shows that the construction industry can contribute to nearly 10% of economics in different countries; the digital twin (DT) has been utilized in many regions and countries such as China, Australia, the United States, and the United Kingdom (Opoku et al., 2021). Hence, the value of DT in the construction industries' project O&M plays a significant role in future sector development, occupational optimization, and work process improvement (Feng et al., 2023).

Meanwhile, DT as the problem detection and decision-making tool has been proven to facilitate data utilization by integrating it with other technologies' data for daily project O&M (Müller-Zhang et al., 2023). As such, DT applications can enhance collaboration through real-time information sharing in many industries, such as architecture, manufacturing, engineering, and construction (Lu et al., 2020a); (Dabirian et al., 2023). In the traditional approach, designers adopt computer simulation and engineering tools to calculate and design project life cycles and physical detecting mechanisms (Chen et al., 2022). They try to optimise the procedure through accurate calculation to save cost, but this method lacks consideration for strategy limitation and the relationship of applicants' configuration. As the computer industry and AI evolved (Gao et al., 2023), DT—a form of improved algorithms and cutting-edge computer technologies—has made real-time monitoring and digital power conceivable. DT can present every physical object, process, and system. It provides a dashboard that can monitor past and present operations and predict future actions by combining software analysis, AI, and machine learning (ML) data, then update any changes in the physical environment (Michie et al., 2017).

DT technology has been applied in several sectors. For example, Xiong et al. (2021) mentioned that NASA was the first organization that applied DT technology to continuously monitor spacecraft status to prevent degradation and failure in 2002. General Electric's (GE) digital department has begun the exploration of a jet engine that can predict the commercial outcome and components' life. Jiang (2021) argued that the service application layer in the field of construction can also display the O&M status of construction lines on a variety of platforms using modules for construction quality presentation, building process control, change management, work progress feedback, device failure diagnosis, health status testing, and O&M. However, a precise knowledge of how to deal with the future direction of integrating DT with current technologies and systems is lacking, as well as comprehensive DT adaption plans (Zhao et al., 2022); (Grüner et al., 2023).

Since the architecture, engineering, and construction (AEC) industries are undergoing a bourgeoning digital transformation, data virtualisation technologies and representation levels have become a new and critical research direction for these industries (D'Urso et al., 2024). Opoku et al. (2021) analyzed the value of DT in six application areas such as facility management, logistics management, monitoring and control, and structural interaction in the project lifecycle. These six segments belong to specific branches of the project O&M, so it proves the importance of DT for upgrading the operational model of the construction industry. As noted by Boje et al. (2020), building information modeling (BIM) provides the protocols for data standards and monitoring activities for sensor networks to increase the added value of equipment data, while DT technology makes use of the synchronization of the bi-directional cyber-physical data flows to reduce the BIM's control capability gap.

Existing studies have focused on the benefits and DT integration with other technologies for organizational performance, facilitating the maturity of digital transformation (Broo and Schooling, 2023). However, the identification or prediction of faults and real-time monitoring of machine equipment operating conditions represent the biggest obstacles to complete automation of machinery and improve project O&M (Deebak and Al‐Turjman, 2022). Even though the quality of project O&M and diverse process flow control can benefit from its application (Zhang et al., 2024), it would not be realized if the basic problems cannot be solved and relevant changes are not appropriately accomplished. Examples include interoperability and standards of data processing within different technologies (Ramonell et al., 2023), challenges of data collection and analyzes for supporting decision-making (Kamari and Ham, 2022), and practical innovations in project O&M procedures for facility managers or O&M managers to enable real-time monitoring and service-based production (Müller-Zhang et al., 2023). The challenges of DT applications in project O&M necessitate its alignment with the organization's strategy and social acceptance which conform to the requirements of digital transformation of project management. Therefore, understanding how to reap the rewards of DT deployment is more crucial than understanding why to use this technology (Love and Matthews, 2019). Several researchers have focused on DT applications for smart construction and carbon emissions in building projects (Yevu et al., 2023), safety management (Agnusdei et al., 2021), building construction industry (Long et al., 2024), and smart buildings (Ghansah and Lu, 2024). Despite previous review efforts, there is limited research related to the application of DT in project O&M. As a result, this study explores the adoption of DT applications in project O&M phase of construction lifecycle processes, and provides research gaps and future research directions that are beneficial to researchers and practitioners and for advancing research in this field.

Given the above, this study aims to conduct a Scientometric and critical review of published articles in the Scopus database related to DT applications in project O&M in the last 10 years (i.e., from 2014 to 2024). Specific research questions that were formulated to achieve the stated aim include:

1) What are the annual research publication trends and relevant peer-reviewed journals on DT in project O&M?
2) What are the scientometric analyses on co-occurrence keywords and documents?
3) What are the mainstream topics identified by DT in project O&M?
4) What are the future research directions on DT in project O&M?

The results of this review could assist researchers, policymakers, and practitioners to enhance the understanding of recent developments and future demands of DT application in project O&M, and how it contributes to the digital transformation of project management. Likewise, the findings can help other researchers to advance potential research directions for DT integration with emerging digital technologies such as AI, blockchain, and IoT, which would facilitate decision-making, fault diagnosis and forecasting in the process of project O&M. Besides, this review study would draw the attention of policymakers and practitioners to the importance of data/information management to enable the application of DT in complex project management scenarios.

The remainder of the review paper is as follows. Section 2 elaborates on the research methodology. The results of the annual publication, relevant peer-reviewed journals, and scientometric analyses are reported in Section 3. Discussions of mainstream research topics, research gaps, and future research directions are provided in Section 4. Section 5 summarises the conclusions of this review paper, while Section 6 highlights its limitations and future research directions.

2. Research methodology

This study adopted a scientometric analysis and critical review method to analyse and virtualise related articles on DT applications in project O&M. An in-depth understanding of the structure and research trends of the studied domain was represented by maps or charts. The Scopus database was used to search for relevant publications and served as a source of data collection. A systematic review was conducted to synthesize the recent and existing research studies. The findings from the critical review would be beneficial for professional knowledge, theories, and promote understanding of research trends. An overview of this review research process is illustrated in Fig.1.

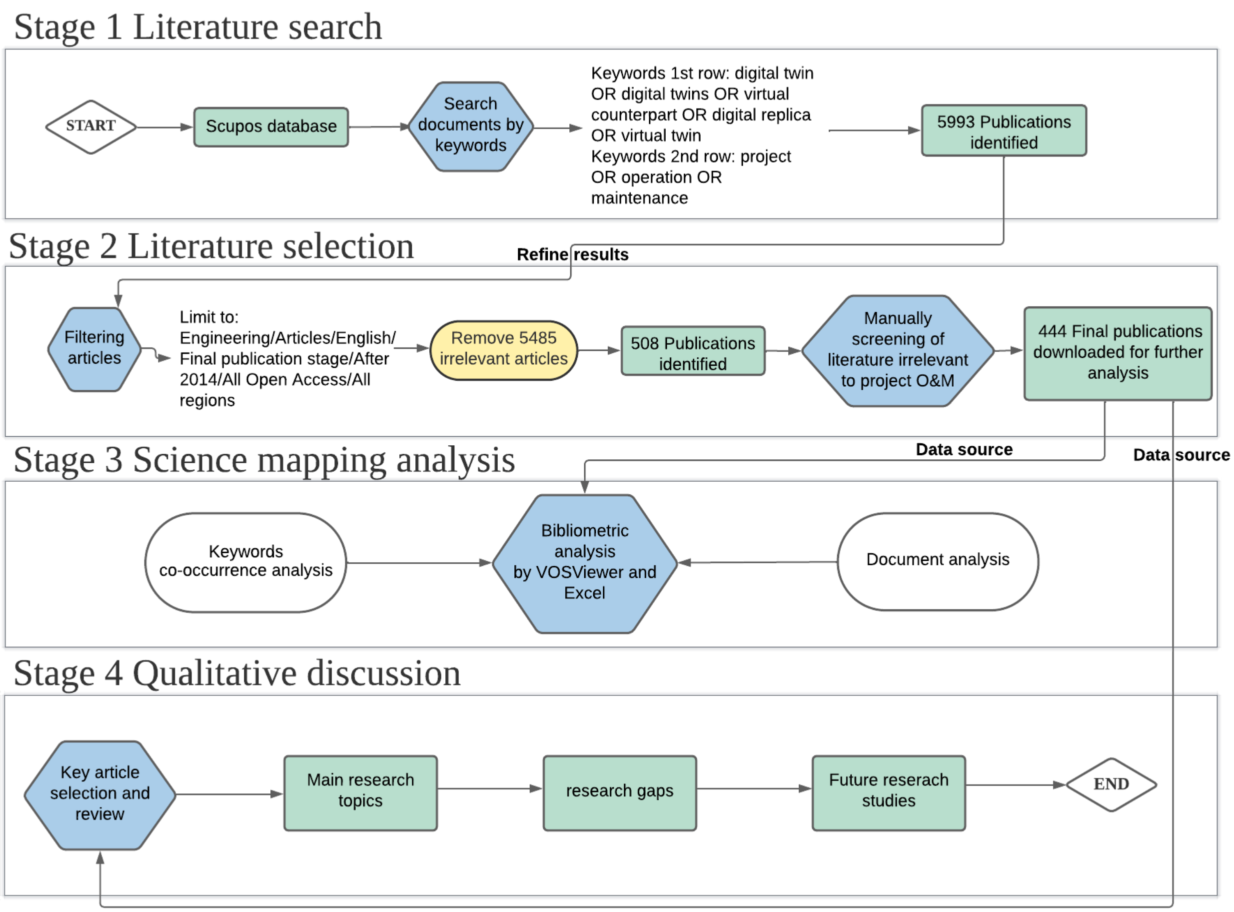

Fig. 1. An overview of the research process

2.1. Stage 1 Literature search

The initial step is to search for relevant publications in the Scopus database that would assist in presenting the results for the annual publication trends and relevant peer-reviewed journals on DT in project O&M. Scopus and Web of Science are the most scientific literature search databases. However, Scopus database covers more broader range of multiple disciplines of journals and articles compared to the Web of Science (Mongeon and Paul-Hus, 2016). Given the interdisciplinary nature of DT applications in project O&M, the Scopus database was selected to capture a wider range of perspectives or diverse disciplines that contribute to the understanding of this study. Furthermore, Scopus has more citation counts and is recognized as performing better than the Web of Science at interface and filtering aspects because it offers advanced citation tracking features for analyzing citation patterns, detailed abstracts and faster indexing for accurate review process (Harzing and Alakangas, 2016). As a result, the Scopus database has been widely utilized in previous scientometric or science mapping review articles (Antwi-Afari et al., 2023; Ye et al., 2024), thus, it was selected for the present review study. A thorough search was carried out using a two-part search string in the Scopus "article title/abstract/keyword" field. The first row of keywords includes "digital twin" OR "digital twins" OR "virtual counterpart" OR "digital replica" OR "virtual twin", while the second row of keywords constitutes "project" OR "operation" OR "maintenance". To ensure that the articles covered the most recent years, the studied period ranges from 2014 to 2024. It can also help to examine the most representative research articles for further analysis.

2.2. Stage 2 Literature selection

After the literature search based on stage 1, the results must be screened to aid in identifying articles within the purview of this study and credible sources that can be used for further scientometric analysis. Considering the studied research domain, the publications were limited to "engineering", resulting to 3,975 publications out of 5,993 literature documents that were initially found by the search query. The document type only included articles. This is because scientific articles undergo rigorous peer review, and they were used to conduct the annual publication trends. Consequently, book chapters, conference papers, reviews, notes, and so forth were omitted, thus obtaining 1,656 publications. Notably, 79 publications were excluded due to "article in press" stage, 39 articles were from trade journals, and 13 book series. In total, 246 irrelevant articles were excluded because they were written in languages other than "English". After selecting all "open access" articles, 508 articles were obtained after the screening processes. Manual screening is imperative to narrow down the application of DT in project O&M because DT has been applied in several sectors such as AEC, aerospace, manufacturing and automotive, especially for flexible assembly line design or redesign. Thus, articles unrelated to the DT applications in project O&M were removed. Meanwhile, other unavailable articles without DOI were also deleted. Finally, 444 articles were used for scientometric and critical review analysis. Table 1 illustrates the search query string and search results.

Table 1. Search strings and results

Query String	**Result**
((TITLE-ABS-KEY("digital twin" OR "digital twins" OR "virtual counterpart" OR "digital replica" OR "virtual twin") AND TITLE-ABS-KEY("project" OR "operation" OR "maintenance")) AND PUBYEAR > 2013 AND (LIMIT-TO (SUBJAREA, "ENGI")) AND (EXCLUDE (DOCTYPE, "cp") OR EXCLUDE (DOCTYPE, "ch") OR EXCLUDE (DOCTYPE, "re") OR EXCLUDE (DOCTYPE, "cr") OR EXCLUDE (DOCTYPE, "bk") OR EXCLUDE (DOCTYPE, "er") OR EXCLUDE (DOCTYPE, "ed") OR EXCLUDE (DOCTYPE, "no") OR EXCLUDE (DOCTYPE, "sh")) AND (EXCLUDE (PUBSTAGE, "aip")) AND (EXCLUDE (SRCTYPE, "d") OR EXCLUDE (SRCTYPE, "k")) AND (EXCLUDE (LANGUAGE, "Chinese") OR EXCLUDE (LANGUAGE, "German") OR EXCLUDE (LANGUAGE, "Russian") OR EXCLUDE (LANGUAGE, "Korean") OR EXCLUDE (LANGUAGE, "Spanish") OR EXCLUDE (LANGUAGE, "Portuguese") OR EXCLUDE (LANGUAGE, "Slovenian") OR EXCLUDE (LANGUAGE, "Italian") OR EXCLUDE (LANGUAGE, "Polish")) AND (EXCLUDE (OA, "publisher full gold") OR EXCLUDE (OA, "repository") OR EXCLUDE (OA, "publisher hybrid gold") OR EXCLUDE (OA, "publisher free2read")))	508
Manually screening literature irrelevant to project operation and maintenance	444

Note: Scopus search was done in January 2024. The standards of irrelevant literature manual screening were described in Section 3.2.

2.3. Stage 3 Science mapping analysis

To comprehensively understand the publications and knowledge in this field, a science mapping analysis was conducted to generate visualized scientometric network diagrams which show the graphical representation of bibliographic records. There are numerous science mapping tools, including BibExcel, CiteSpace, CoPalRed, Gephi, IN-SPIRE, VOSviewer, and many others, designed for analyzing and visualizing the bibliometric network of scientific research (Kumar and Choukimath, 2015; Wu et al., 2020). The VOSviewer tool was selected because it offers text-mining functionalities and can create co-occurrence networks from scientific literature. VOSviewer autonomously detects terms and constructs scientometric maps using web data, which provides clear graphical representation and facilitates analysis from diverse perspectives (Van Eck and Waltman, 2017). The key advantages of VOSviewer over other science mapping tools encompass its user-friendly graphical display capabilities, suitability for handling large datasets, and flexibility in accommodating diverse databases and sources in various formats (Van Eck and Waltman, 2010; van Eck and Waltman, 2017). Consequently, VOSviwer was adopted in this study to generate and visualize network maps of DT applications in project O&M in order to conduct (1) keywords co-occurrence analysis and (2) document analysis. Keyword co-occurrence analysis examines the number of articles associated with the emerging keywords, while document analysis displays the number of citations of a documents (Van Eck and Waltman, 2010). These results were further used to understand and discuss the mainstream topics, research gaps and future research directions of DT in project O&M.

2.4. Stage 4 Qualitative discussion

This stage will speciously analyze the contents of key selected articles related to the theme of DT in project operation and maintenance, whose objective is to thoroughly assess this study's goals associated with the popular study subjects in the field of DT in project O&M in the construction industry. The results are obtained by VOSviewer and are based on a review of relevant publications, data visualization, and temporal classification. Meanwhile, the most cited articles analysis and keyword analysis can indicate the hot topics and research trends of DT application in project O&M. The goal of assessing DT usage in the construction sector and establishing practical application in project O&M is to highlight the difficulties and problems so that relevant researchers and professionals may use them as a guide for future development directions. After the manual screening, the 444 articles that passed muster will be subjected to a thorough qualitative analysis that compares and discusses the annual publication trend of articles, relevant peer-reviewed journals, keywords co-occurrence analysis, and document analysis. In this stage, the mainstream research topics in DT in project O&M were discussed based on the keywords and identified documents in the previous stages. It also articulates future research directions and research gaps that are of great value to be further researched for the development of DT applications in project O&M.

3. Results

3.1. Annual publication trend of articles

In this study, 444 journal articles were used for further analysis as distributed in Fig. 2. As such, Fig. 2 shows the annual publication trend of articles related to DT applications in project O&M. As shown in Fig. 2, the articles were published from 2014 to 2024. It clearly shows a significant overall upward trend of number of published articles on DT applications in project O&M from 2017 to 2023. The increase in number of publications may be explained by the advancement of digital technologies and the growing interest of practitioners and researchers in this field. For instance, the maturity of BIM applications and the development of AI technologies have promoted the demand for real-time monitoring, predictive fault diagnosis, and prevailing visualization dashboards. Likewise, the transformation of digital technologies in project management, especially the O&M stage requires more accurate and efficient digital technologies to manage facilities and their operational processes. As a result, researchers and practitioners have demonstrated the integration of BIM and DT for data modelling, assessment, and collection (Pan and Zhang, 2021; Radzi et al., 2024). It was found that the number of published articles increased in the last 4 to 5 years and peaked at 195 articles in 2023. Based on the continued growth published articles in the studied domain, it is expected that the number of publications will increase in 2024, since the data was collected as of January 2024, showing a downward trend from 2023 to 2024 with 17 articles. The future research could necessitate to confirm whether the speculation is correct.

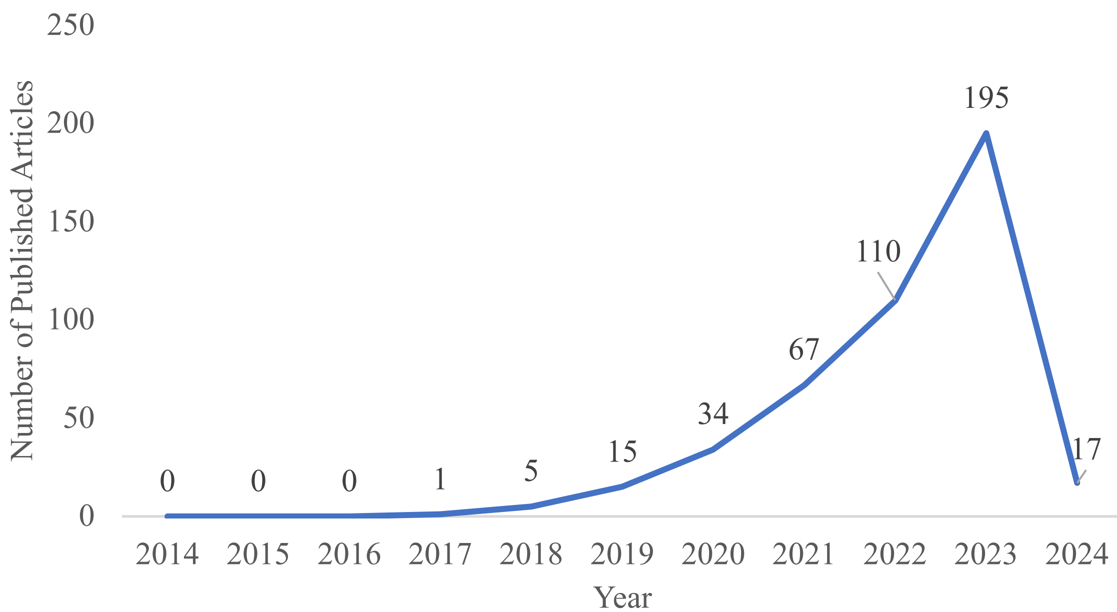

Fig. 2. Annual publication trend of articles in DT in project O&M (A total of 444 articles)

3.2.Selection of relevant peer-reviewed journals

After manual screening, 444 articles related to DT in project O&M have been selected and will be specifically analysed through the following bibliometric analysis. Table 2 shows the top-ranked 20 journals according to the number of published articles based on the 444 selected articles in this review study. It was found that "*Automation in Construction*" contributes to the largest number of articles at 23, occupying 5.18% of the total publications. The scope of "Automation in Construction" journal includes articles focusing on all stages of project lifecycle, with dedicated interest in digital transformation research pertaining to computer-aided decision support systems, product data interchange, facilities management, and intelligent control systems. This may be reason why researchers and practitioners who are interested in DT applications in project O&M choose to publish their articles in "*Automation in Construction*". Six peer-reviewed journals listed in Table 2 have published not less than 10 articles each, indicating that these journals also focused on research related DT in project O&M. Overall, these analyses were based on 444 articles from 174 journals, indicating that these journals can be represented as further reference values of DT research.

Table 2. Top 20 selected peer-reviewed journals, 2014 to 2024.

Journal name	**Number of relevant articles**	**% of total publications**
Automation in Construction	23	5.18%
Journal of Manufacturing Systems	16	3.60%
International Journal of Computer Integrated Manufacturing	13	2.93%
Robotics and Computer-Integrated Manufacturing	11	2.48%
Computers in Industry	10	2.25%
The International Journal of Advanced Manufacturing	10	2.25%
Energy	9	2.03%
Mechanical Systems and Signal Processing	8	1.80%
Sustainable Cities and Society	8	1.80%
Cirp Annals	7	1.58%
IEEE Transactions on Industrial Informatics	7	1.58%
Journal of Computing and Information Science in Engineering	7	1.58%
Reliability Engineering & System Safety	7	1.58%
Advanced Engineering Informatics	6	1.35%
Applied Energy	6	1.35%
Building and Environment	6	1.35%
Computers & AMP; Industrial Engineering	5	1.13%
Energy and Buildings	5	1.13%
Journal of Cleaner Production	5	1.13%
Journal of Computing in Civil Engineering	5	1.13%
Total	**174/444**	**39.19%/100**

3.3.Keyword co-occurrence analysis

Keywords are representative and refined expressions of the content of a research article. Keyword co-occurrence analysis allows for identifying hot topics and research areas in the knowledge domain over a specific period. In VOSviewer, keywords are based on the co-occurrence analysis of 444 records. The author keyword marks the keyword provided by the author. The distance between the two nodes represents the strength of the relationship between the two research areas. The further the distance, the weaker the relationship between each other. After merging the agreed keywords using the VOSviewer thesaurus file, it was concluded that out of 1582 keywords, 35 items met the criteria as each word's minimum number of occurrences was set at 4. This threshold was chosen after several attempts were made to obtain the best clusters for various other factors. Fig. 3 shows the keyword co-occurrence network with 35 items, 105 links, and 296 total link strengths.

The node's size indicates how frequently a keyword appeared in the data file. The top two most frequently occurring keywords are "digital twin" (occurrence=320) and "internet of things" (occurrence=21). These two keywords are advanced digital technologies which can be integrated to enhance the digital transformation of project O&M, thus revealing why they are the most frequently occurring. Additionally, certain keywords had relatively high total link strength scores, which indicates a stronger connection between the keywords and the topics and themes such as the top five in total link strength score, "digital twin" (total link strength=209), "internet of things" (total link strength=42), "Industry 4.0" (total link strength=31), "condition monitoring" (total link strength=26), and "predictive maintenance" (total link strength=22). These results indicate that DT is often connected to IoT as the new paradigm of Industry 4.0 for numerous project O&M scenarios. It also reveals the continued development of Industry 4.0 in a large-scale and fast-growing IoT market, which utilizes IoT and DT to facilitate the realization of Industry 4.0. Nevertheless, "condition monitoring" and "predictive maintenance" are the two primary critical success factors for DT applications in project O&M (Jiang et al., 2021). Since Industry 4.0 promotes the agenda of digital transformation, the potential of DT in project O&M has been discussed (Radanliev et al., 2022). By integrating DT and other digital technologies, the condition monitoring and predictive maintenance at project O&M stage could be realized, thus explaining why these keywords had higher total link strength. The frequency of keyword occurrences is usually proportional to the total link strength. These items also indicated that these were popular topics in the project O&M field's digital twin during the years of research.

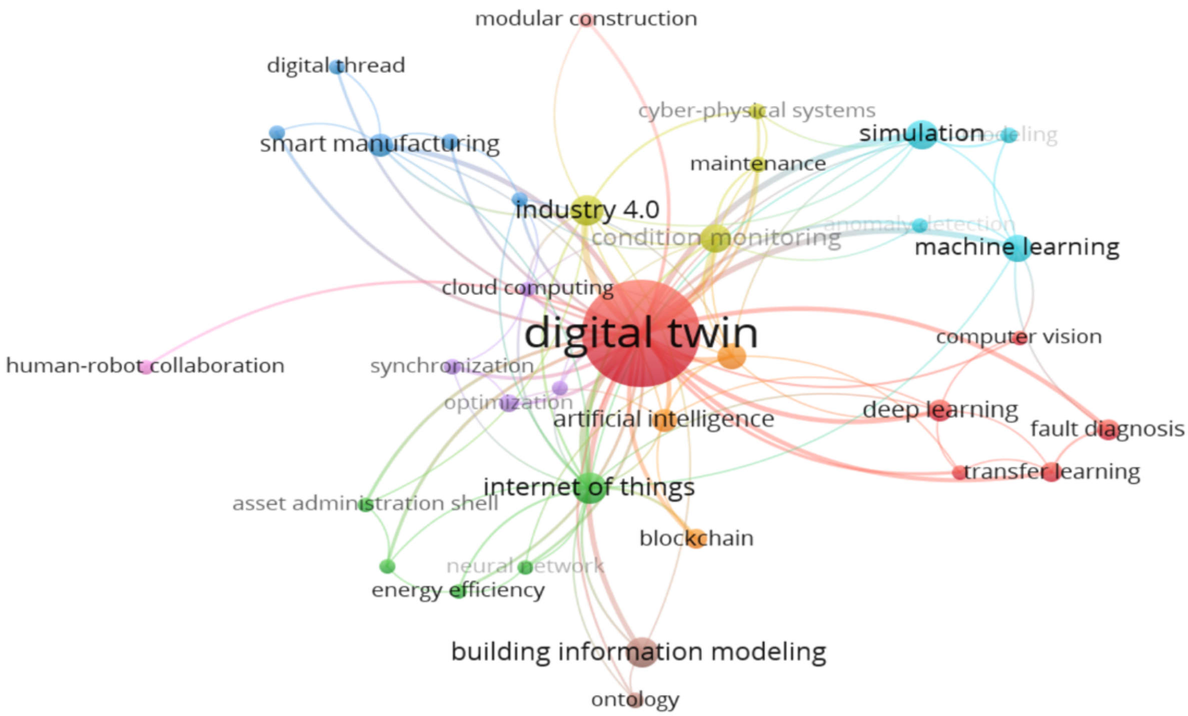

Fig. 3. Keywords co-occurrence network of DT in project O&M

Table 3 summarises the keyword co-occurrence and each node's strength. It reveals how frequently the keywords are retrieved from the literature. It is obvious that "digital twins", "internet of things" and "industry 4.0" appeared more frequently than others, which means these keywords are widely associated and analysed in DT in project O&M. The average publication year also reveals that the research in this area has been immensely popular in the last two years and the research intensity has been on the constant upswing stage. For example, it was only "cyber-physical systems", "cloud computer", and "service-oriented architecture" these two keywords occupied the year 2020, then 4 keywords related to the function of DT, such as "simulation", "modelling", "industry 4.0", and "maintenance" frequently emerge in 2021, more comprehensive research expansion in this area happened in 2022 (keywords=20) and 2023 (keywords=8). Keywords show the interconnection and interoperability research with other digital technologies, such as "blockchain", "BIM", and "IoT", etc.

The links are the number of linkages with another keyword, and the total link strength can show the degree of strength with a specific node. As shown in Table 3, most keywords' total link strength is lower than 20. Only the more general keywords expression about the DT function in project O&M, which commonly happens. VOSviewer provides a dynamic period view for keyword research. Even though the keywords have been concentrated in the last four years, it is worth noting that keywords such as "deep learning", "machine learning", "transfer learning", and "neural network" belong to the category of complex computer science and AI development. Besides, "maintenance" and "cloud computing" exist relatively early and rank the highest average citations at 140.8 and 84.25, respectively. It slightly implies that digitalised maintenance demand increased in recent years. The technologies represented by these keywords are all linked to DT in the construction industry, and the other areas of project O&M applications and development provide the basic equipment conditions and data model basis.

Regarding the average normalised citations, "cloud computing" still ranks the highest at 2.68 in Table 3. This means that these keywords are cited the most on average. It shows that the average citations are disproportionate to the average normalised citations. For example, the average normalised citation of "smart manufacturing" is the highest, and the highest keyword based on average citations is "maintenance". It indicates that computer science and complex digital technologies have changed traditional operation methods and have become more intelligent for the construction and manufacturing sectors. Using advanced robotics and model work techniques will enhance the need to adapt human-machine interaction strategies, interconnection of multi-technologies, and workflows.

Table 3. List of keywords of co-occurrence analysis

Keywords	**Occurrences**	**Links**	**Average publication year**	**Average citations**	**Average normalized citations**	**Total link strength**
Digital twin	320	34	2022	20.25	1.06	209
Internet of things	21	18	2022	27.90	1.30	42
Industry 4.0	20	12	2021	37.30	1.35	31
Condition monitoring	17	10	2022	42.35	0.81	26
Predictive maintenance	14	11	2022	35.43	0.98	22
Simulation	18	8	2021	15.94	0.37	21
Machine learning	16	7	2022	18.75	0.89	19

Smart manufacturing	11	7	2022	44.27	2.20	16
Deep learning	10	7	2023	18.80	0.88	15
Artificial intelligence	11	7	2022	23.73	1.29	14
Building information modeling (BIM)	20	4	2022	32.20	1.45	13
Cloud computing	4	7	2020	84.25	2.68	12
Fault diagnosis	9	3	2023	4.22	1.22	11
Transfer learning	8	4	2023	3.38	0.49	11
Blockchain	8	3	2022	32.00	2.02	10
Sensors	4	7	2022	11.50	0.36	10
Optimization	6	4	2022	6.17	0.52	8
Synchronization	5	4	2022	22.40	1.14	8
Cyber-physical systems	5	4	2020	67.60	1.23	7
Maintenance	5	4	2021	140.80	2.44	7
Energy efficiency	4	4	2022	19.00	1.37	7
Fatigue	4	4	2022	9.75	0.77	7
Remaining useful life	4	4	2023	5.75	0.67	7
Service-oriented architecture	4	4	2020	48.75	0.94	7
Anomaly detection	4	3	2022	29.75	1.54	6
Asset administration shell	4	3	2022	26.25	0.64	6
Neural network	4	4	2023	2.25	0.78	6
Virtual reality	5	3	2022	3.00	0.37	5
Modular construction	4	2	2022	12.50	1.70	5
Reinforcement learning	4	2	2023	2.75	0.95	5
Modeling	5	3	2021	17.20	0.44	4
Ontology	5	3	2023	9.20	0.97	4
Computer vision	4	3	2023	6.50	0.89	4
Digital thread	4	2	2022	12.75	1.75	4
Human-robot collaboration	4	1	2022	14.00	1.11	3

3.4 Document analysis

Setting the minimum citation number of a document to 50, 34 meets the threshold out of 432 documents. The detailed top 15 most normalised citation articles have been listed in Table 4, and it was found that Feng et al. (2023) study got the most normalised citations at 27.15 but relatively middle-level citation numbers at 82. This article was published in 2023, the newest among other articles, so that it might be the reason for the lower citation number. It indicates that DT significantly affects asset fault diagnosis or condition monitoring through intellectual property. Some articles integrated DT with BIM and other technologies like blockchain and human-robotic interaction to increase the efficiency of the construction and manufacturing industries. From Table 4, the articles of Pan and Zhang (2021), Lee et al. (2021), and Aheleroff et al. (2021) are all related to project management and service system design, which expresses the DT application research is more focused on the managerial process and procedures, especially in the year of 2021.

Subsequently, the articles in Table 4 indicated that the DT research has integrated with the existing technologies implemented in the construction industry, such as BIM, IoT, and blockchain technology. To better develop DT in project O&M in this industry, He et al. (2021), Lee et al. (2021), Zhu et al. (2020), and Wang et al. (2021, 2022) developed DT integration with other technologies to enhance the historical data support and existing technologies application efficiency. Likewise, smart city design and management are driven by the DT and incumbent digital technologies to control traffic and monitor city conditions, which can be shown by the articles of Xia et al. (2022) and Zhu et al. (2020). Besides that, the articles about DT function in project O&M, such as asset management, facilities health condition prediction, and fault diagnosis, become more crucial and mature, even connecting with specific case studies. This can be seen in the articles of Luo et al. (2020), Tao et al. (2018), Stark et al. (2019), and Booyse et al. (2020).

Fig. 4 illustrates the document network analysis. From this figure, the front and size of the nodes stand for the citation number of each article. It was found that Tao et al., 2018 got the most citations at 489 with a lower level of normalised citations at 2.86. This article was published in 2018, which is a relatively earlier publication. As such, this article received much attention in the expertise field. As shown in Fig. 4, many single nodes represent many articles with fewer citations and no links to other articles, which may also be a sign that the research topic of these standalone articles still needs to receive more attention than other articles.

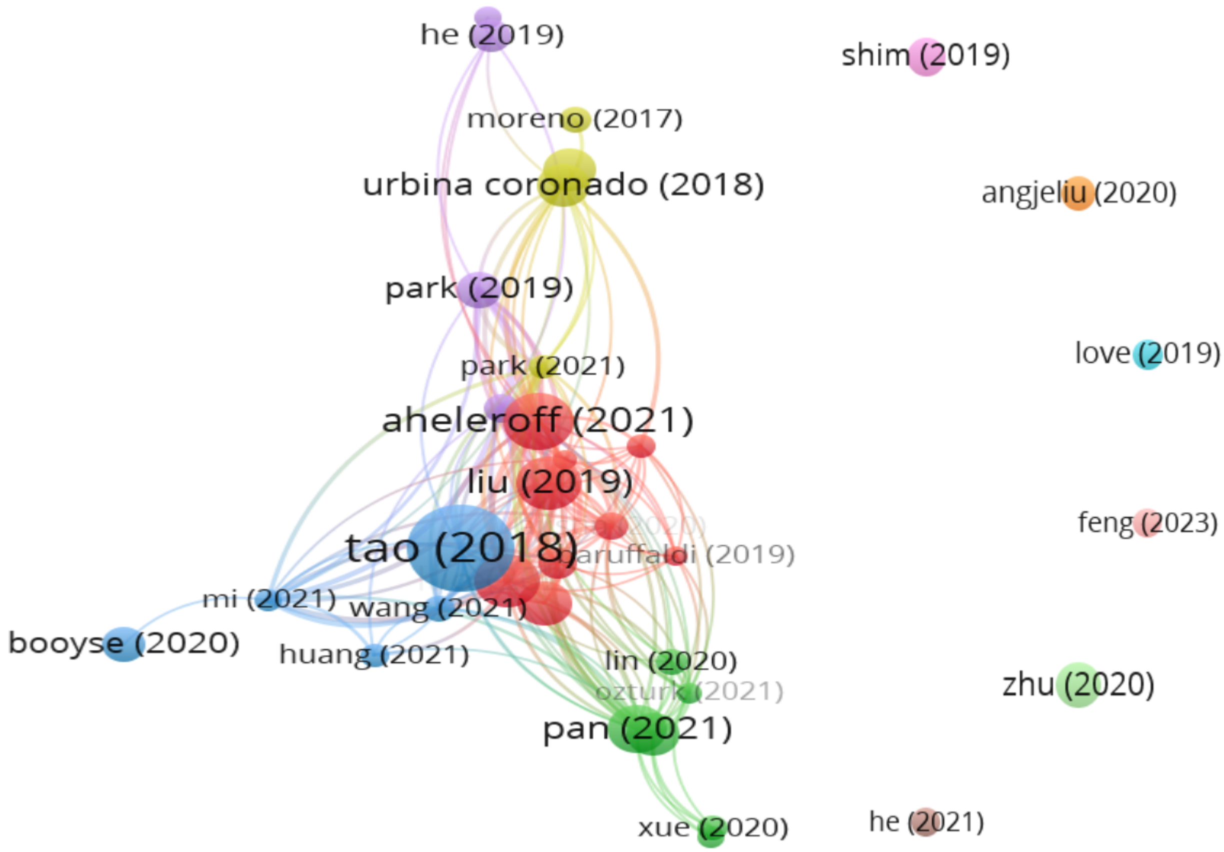

Fig. 4. Document network analysis of DT in project O&M

Table 4. Top 15 cited articles among 444 articles, 2014-2024

Articles	Titles	Citations	Normalized Citations
Feng et al. (2023)	Digital Twin-Driven Intelligent Assessment of Gear Surface Degradation	82	27.15
Li et al. (2022)	Digital Twin in Smart Manufacturing	164	11.72
Aheleroff et al. (2021)	Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model	257	8.44
Pan and Zhang (2021)	A BIM-Data Mining Integrated Digital Twin Framework for Advanced Project Management	193	6.33
Lee et al. (2021)	Integrated Digital Twin and Blockchain Framework to Support Accountable Information Sharing in Construction Projects	166	5.45
Luo et al. (2020)	A Hybrid Predictive Maintenance Approach for CNC Machine Tool Driven by Digital Twin	227	4.42
Xia et al. (2022)	Study on City Digital Twin Technologies for Sustainable Smart City Design: A Review and Bibliometric Analysis of geographic information system and building information modeling integration	60	4.29

Zhu et al. (2019)	Parallel Transportation Systems: Toward IoT-enabled Smart Urban Traffic Control and Management	166	3.23
Liu at al. (2019)	Digital Twin-driven Rapid Individualised Designing of Automated Flow-Shop Manufacturing System	227	2.88
Tao et al. (2018)	Digital Twin Driven Prognostics and Health Management for Complex Equipment	489	2.86
He et al. (2021)	BIM-enabled Computerized Design and Digital Fabrication of Industrialized Buildings: A Case Study	84	2.76
Wang et al. (2021)	Digital Twin for Human-Robot Interactive Welding and Welder Behavior Analysis	80	2.63
Booyse et al. (2020)	Deep Digital Twins for Detection, Diagnostics and Prognostics	124	2.41
Stark et al. (2019)	Development and Operation of Digital Twins for Technical Systems and Services	177	2.24
Park et al. (2021)	The Architectural Framework of a Cyber-Physical Logistics System for Digital-Twin-Based Supply Chain Control	67	2.20

4. Discussion

After reporting the results of this review study, this section will mainly focus on the main research topics, research gaps, and future research studies within the theme of DT in project O&M. Although previous studies on DT were primarily conducted in other disciplines such as automobile, manufacturing, the current review paper focuses on the construction sector, which is the research hotspot topics in recent years and caused significant interests of scholars and industrial participants. The construction sector is typically project-based, its O&M involves multiple stakeholders and complex project task requirements. Nevertheless, we cannot discount the value that DT will bring to the construction sector and the development of project management, which also affects the reference value of this review paper.

4.1. Summary of the main research topic of DT in project O&M

The main keywords of the given topic have been listed in Table 3. There are inner links between keywords such as DT, deep learning, computer version, and fault diagnosis. In most occurrences, more keywords are related to other emerging technologies, such as blockchain technology, AI, BIM, virtual reality (VR), etc. These are the basis of industry intelligent transformation, enabling changing the O&M procedure and processes while operating real production activities. Section 4.4

has illustrated the detailed keyword clusters, and the mainstream themes and topics can be summarized below.

4.1.1. DT-based artificial intelligence (AI) technology for project O&M

Emerging technologies such as AI and its function enrich DT application efficiency and advantages, which attract significant attention. As shown in Table 3, AI, deep learning, transfer learning, and ML are all ranked at a relatively higher occurrence level. DT enables the real-time virtual and real-world connection with the fault diagnosis and prediction functions to optimize the project O&M processes and outcomes. Based on data science and AI technology development, complex and large numbers of engineering machines and equipment data can be analyzed in different AI models. For example, deep learning, as the new generation of AI technology shows obvious advantages in feature extraction, intelligence level, and knowledge-learning aspects (D'Urso et al., 2024). Many experts are exploring integrated DT with their specific AI models to monitor machine health conditions and predict their longevity through historical data dynamic comparison (Zhang et al., 2023c), then facilitating the reliability of managers' O&M decision-making. DT provides the simulation environment to train the AI algorithms and models, which is similar to people learning knowledge to solve O&M problems (Bordegoni and Ferrise, 2023). For example, to increase the DT data efficiency and accuracy, control the data collection costs, solve data latency problems (Gao et al., 2023), and enlarge the DT application scale in the real industrial production process, Xia et al. (2023) developed DT integrated with transfer learning and cloud-based model to diagnosis the faults of DC/DC converter to support power supply systems maintenance strategy setting in time. On the other hand, the simulation model and analysis of ML require plenty of time to execute them, which limits the models' application, but DT's virtual world duplicates the physical world becomes a perfect place to modifier and develop AI models application, then improve the production and operation efficiency (Jain and Narayanan, 2023). These two emerging technologies integration solve application and research challenges from both sides and generate reciprocal effects.

While project O&M is the longest and most complex project stage, it usually involves multiple machinery equipment, facilities, people engagement, and daily building space systems management to ensure the function of the building executes efficiently and fulfills the demands of project customers and users (Zhao et al., 2022). Table 3 also incorporates the keywords like "cloud computing", "remaining useful life" and "service-oriented architecture". AI and DT technologies application sufficiently renew project O&M methods and generation, facility and project managers are assisted by these emerging technologies to design equipment management and operation plans and support intelligent, scientific, feasible decision-making on maintenance strategies (Zhang et al., 2023a). The powerful arithmetic of AI can replace manual information search and analysis. For instance, when emergency circumstances happen in the building, DT models can align with BIM (Pan and Zhang, 2021), information communication technology (ICT), and mixed reality (MR) (Wu et al., 2022) etc., to aid real-time workforce safety identification, facilities health monitoring, and fault diagnosis in a real-time.

4.1.2. DT-enabled smart city and sustainability

Since emerging technologies have brought changes to the traditional construction methods and concept of urban architecture. From a macro perspective, smart city O&M also plays a crucial role in space intelligence. Given the advantages of DT technology for real-time operational and fault prediction capabilities, numerous areas are investigating in-depth applications for smart manufacturing, smart energy, and smart homes. The smart city relies on IoT, GIS, BIM, AI, and other technologies in the industry 4.0, and 5.0 environment to reduce operational human involvement through an intelligent method to realize the sustainable urban O&M, it is a symbol of the urbanization process which increases the security, cost-saving, and intrinsic connections of the city (Silva et al., 2018). Bujari et al. (2021) designed a distributed geographic system for different cities' heterogeneous data absorption and analysis to consider potential interruptions of daily city operation stakeholders through DT, cyber-security systems, and big data.

Another research theme is traffic network optimization, as the climate change and traffic flow issues, DT technologies are associated with GIS and other geographic technologies to realize real-time traffic network monitoring and modification. AI and IoT-supported smart traffic systems were developed by Zhu et al. (2019) through a large number of iterative data simulations over a long period are used to predict the operational outcomes that may come out of specific cases, and then to plan, design, and operate and maintain the smart urban traffic system control. City transport infrastructure maintenance, such as bridges, roads, and railways, all can be operated and maintained through DT-enabled data-driven methods (Wang et al., 2023). In addition, the keywords such as "anomaly detection" (Lu et al., 2020b), "sensor", "synchronization", etc. emphasize the real-time data update and facilities fault diagnosis function of DT, so there are some researchers are exploring DT applications for city heritages maintenance.

Sustainability indicates the reducing of product lifecycle emissions, pollution, and consumption, and the improvement of the accompanying environmental, economic, and social benefits (Zhang et al., 2021). DT utilized for energy performance monitoring and prediction maintenance has been broadly discussed and researched as the key part of energy system digitalization and optimization. Zhang et al. (2023b) renewed the heating, ventilation, and air systems of heritage buildings through sensor configuration to enhance energy consumption and air quality management. Numerous articles discussed how industry 4.0 has impacted city design and construction due to issues with resource utilization, increased energy efficiency and hazardous waste disposal, and living aspects, then facilitating city sustainability O&M (Safiullin et al., 2019).

4.1.3. DT applications for project asset management

DT application in project asset management has been broadly explored in the manufacturing, energy, and construction sectors (Edwards et al., 2023). Table 3 presents keywords like "asset administration shell" and "human-robotic collaboration" articulating the essential function of DT in asset management. As civil engineering inevitably requires equipment/plant, how to efficiently utilize and maintain this large equipment is also a germane topic. DT integrated with the IT systems and BIM models to upload the operation costs details, assets health commission brochure generation for operators, and then construct a user-centred dashboard for various stakeholders to master asset status from the whole lifecycle (Keskin et al., 2022). Besides that, the operational workflow design in the DT environment not only relies on sensors' data transmission but also on assets' attributional and historical data consisting of the asset administration shell for the asset operators to understand the data-driven workflows and demands (Grüner et al., 2023). DT applications for asset management still need to consider the operational cost and capital cost benefits and how digital technologies transform traditional commercial activities to achieve more business value (Love and Matthews, 2019).

Although human-robot collaboration (HRC) has been discussed over recent years, there are still more studies that need to be conducted by combining the recognition and physical levels of humans and robot collaboration to realize common goals (Sun et al., 2022). Current research focused on ML technology utilization in the process of HRC. Semeraro et al. (2023) stated the categories of collaboration tasks and claimed the importance of the usage of time-dependency ML. Wang et al. (2024) developed a framework to train DT data based on a neural network, then test it in the physical system to improve the feasibility of human-robotic collaboration safety. Choi et al. (2022) mentioned an original creation of an integrated system based on mixed reality (MR), deep learning, DT, 3D point cloud data, and HRC to real-time secure human safety while working which can be implied in the daily project O&M scenes. Safety management should be updated within the HRC working framework because the safety standards have changed. The HRC's relevant safety standards such as DIN ISO 10218-1&2 or ISO TS 15066, which can implicate different sorts of standards can complicate the operational procedure and require more measurement efforts. DT as the duplication version of the physical world provides a perfect platform for safe robotic algorithm development (Baratta et al., 2023).

4.1.4. Blockchain integrated DT for project O&M

Blockchain can be regarded as the distributed ledger technology and asymmetric encryption technology, which ensures that decentralized transaction data can be recorded and shared traceably, immutably, and transparently (Adu-Amankwa et al., 2023). Each participant can be a node, which is operated by computer servers. Then, the smart contract is a digital type of contract codification and execution, once the conditions of the smart contract are met, the payment mechanism is automatically triggered. Blockchain has been broadly explored in Finance, Retail, Public institutions, and construction sectors. Due to the fragmented, complex, and uncertain features of construction projects, blockchain-enabled information sharing and decentralized organizational structure can help tame complexity (Papadonikolaki and Jaskula, 2023) and ensure computer algorithm-based governance. DT transports the building information in real-time to the blockchain, then all the transaction data is traceable and immutable recorded with a timestamp, which facilitates various project stakeholders' responsibility clarification and understanding (Lee et al., 2021). A study by Lee et al. (2021) also ranked at a high level in Table 4. Blockchain sometimes is mainly used to guarantee the trustworthiness of DT data, for its historical data will be overwritten in the dynamic asset O&M process (Tavakoli et al., 2023).

In addition, blockchain-enabled DT technology assists cross-disciplinary stakeholders' collaboration and breaks information island in the process of construction, resource leveling, information tracking, and task execution guidance and alarm can all be utilized by DT in a timely order (Jiang et al., 2023). Contract management, project quality management, and even the whole lifecycle management can be shaped by blockchain-enabled DT technology. In a word, blockchain enables collaboration within the heterogeneous social, network, and physical space resources (Li et al., 2023).

However, blockchain and DT mobilized the transaction methods and information-sharing traditions, but as the disputed technologies, the project-based organization structure and governance approaches influence stakeholders' relationship establishment also attract many discussions. Qian and Papadonikolaki (2021) concluded that blockchain can promote trust relations from many dimensions and shift relation-based trust to cognitive and system-based trust in the supply chain management field. Blockchain and DT utilization as a decision-making support tool in the complex logistic and inventory management process exerted an efficient function as well (Pan et al., 2021) (Gai et al., 2022). Subsequently, stakeholders' acceptance, operation capability, and technological understanding still hinder the real application in the construction sector.

4.1.5. DT for advanced project management

The digitalization degree of construction project management is still under a transition process. Digital technologies such as IoT, BIM, VR, MR, ICT, and others all contribute to the transition progress while DT exceedingly promotes the development of advanced project management with all these digital technologies. It enables the project O&M process to automate and eliminate the procedures that involve human intervention to construct event diary logs and evaluate procedures' performance (Pan and Zhang, 2021). There are some keywords and articles primarily pertinent to the function of DT in Table 3 and Table 4, such as "fault diagnosis", "predictive maintenance", "condition monitoring", "Synchronization", "Service-oriented architecture", "fatigue", "optimization", and "anomaly detection", which indicates how DT contributes to project O&M, then, further to advanced project management. Feng et al. (2023) designed a DT model to assess the gear surface degradation situation, whilst Booyse et al. (2020) studied the trace degradation of the asset lifecycle situation through response to the asset data simulation model. A study by Dreyer et al. (2021) implemented DT to examine the energy pipelines' fatigue and health situation, instead of periodic stopping of equipment for piping equipment assessment.

Project complexity and uncertainty always challenge the performance and success of projects, O&M is the longest stage, and the complex degree is relatively high, many articles also mentioned modular construction integrated with VR (Wu et al., 2022) and DT. DT can be used to monitor on-site assembly situations and the modular installment process. DT and VR as the immersive training and simulation platform for the robot arrangement in the modular construction will mitigate the construction on-site complexity degree and increase the safety measurements (Zhu et al., 2022).

In the case of decision-making bias and optimization bias of project operators and managers, DT-driven decision-making is based on event simulation and precise data calculations, which enhance the feasibility and accuracy of decisions. For example, Fang et al. (2024) developed a highway infrastructure rebuild, recovery, and operation decision support visualized platform and framework by DT for the project and government decision-makers. Decision-making is one of the key elements of project governance, which will severely affect the project's performance and success, as well as the satisfaction degree of end users and project clients (Müller-Zhang et al., 2023). Risk identification and mitigation strategy suggestions provided by DT real-time structure health monitoring and predictive maintenance then assisted the service-oriented structure construction (Shi et al., 2023). Project O&M processes are generally becoming a service provision process. DT implementation conspicuously improves the efficiency and productivity of project O&M, then contributes to the advanced project management knowledge fields and empirical project practice.

4.2. Research gaps of DT application in project O&M

The following subsections describe in detail the six main research gaps of DT application in project O&M based on the identified mainstream research topics. The contents of each are presented in Figure 5, which briefly summarizes the limitations or challenges of DT application.

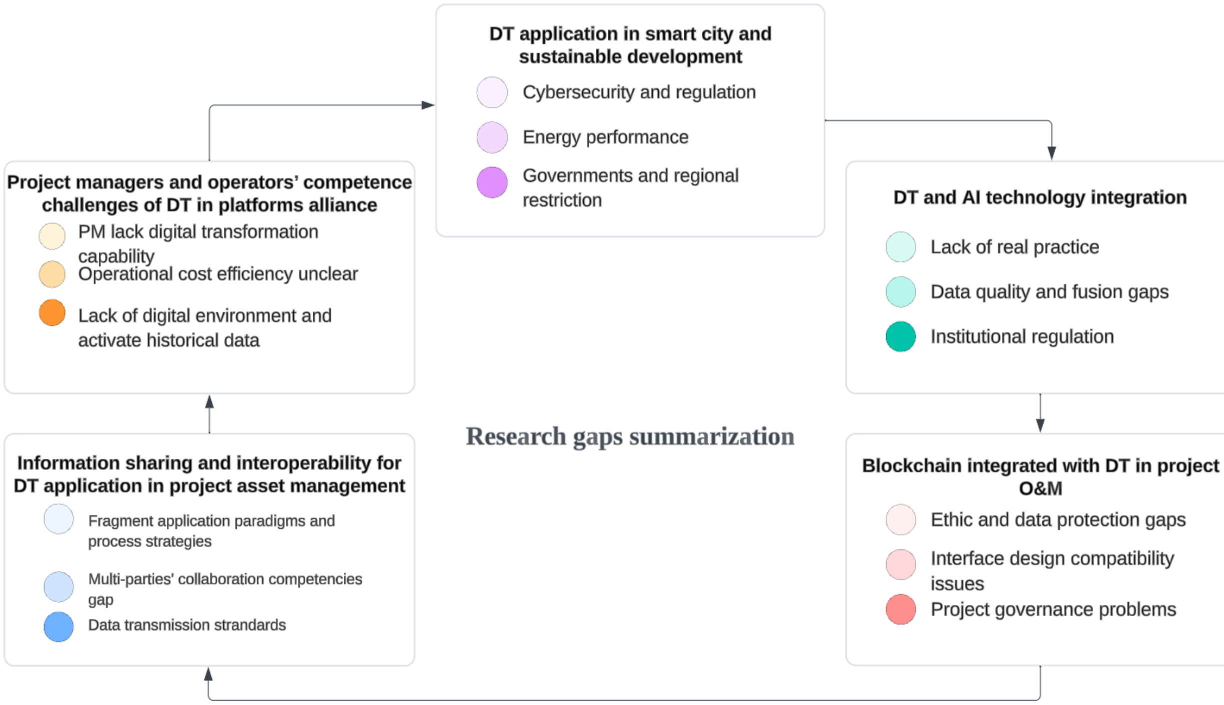

Fig. 5. Research gaps of DT application in project O&M

4.2.1. Scenarios of DT and AI technology integration in project O&M

DT and AI technology have been utilized in many areas, such as smart manufacturing, smart cities, and aerospace fields. There are three main stages of AI+DT implementation in project O&M. The first stage is monitoring and observation, through the DT platform to realize the whole project lifecycle and asset health condition monitoring in a real-time, complex project O&M scenarios problems can be found and fixed with the power of arithmetic and knowledge of AI technology. The second stage is prediction and forecast, after detailed data collection, the simulation models of project participants and O&M equipment can be built to get the simulation results for different project tasks and events. The third stage is evaluation and decision optimization. The multiple simulation possibilities calculation and comparison assisted by deep learning etc. technologies to design optimized plans and strategies (Lv and Xie, 2022). However, the intelligent project on-site construction environment and procedure planning require a large amount of data on building, workflow, and operators' collaboration. Many AI+DT applications in project O&M primarily proposed concept models without real practice and testing in industrial production scenarios (D'Urso et al., 2024). From the managerial angle, the analysis capability of the AI systems can only execute the designed tasks, but lack of lesson learned reflection, performance enhancement depends on the historical data accuracy and completeness. The general project management regulation for AI and DT applications needs to be refined (Müller et al., 2024).

4.2.2. Challenges for DT application in smart city and sustainable development

By 2050, the urban population is expected to increase by 2.5 billion, according to the United Nations, it can be inferred that the significance of smart cities and the associated intelligent solutions will rise significantly, even though changes in how cities function and live are closely related to the region's politics, economy, traditions, and culture (Popović and Rajović, 2021). Industry 5.0 will promote the intelligent degree of the population's urban life, but the traditional architectural structure limits the implementation of emerging technologies, furthermore, it will affect the realization and sustainable development of the smart city. Smart cities necessitate a protracted process for changing how current urban buildings are maintained and operated, but the contemporary architectural designs' capacity for sustainability, energy conservation, extreme weather, and geohazard prevention and control will undoubtedly grow (Goyal et al., 2020). Digital transformation of incumbent buildings will be certainly constrained by governments of different countries, technical feasibility, social collaboration, and economic benefit (Tomičić Pupek et al., 2019). Hence, it is necessary to consider the detailed smart city initiation and supporting O&M measures as much as possible in the construction design phase, and the data-oriented lifestyle must be suitable for future technology upgrades. Meanwhile, it is imperative for the designer and construction workers to consider the overlapping and duplicating parts of technical functions to avoid high input costs and low economic efficiency.

Smart city statistics accumulated for DT model construction are essential, but cross-region city data collection and interconnection are under development due to data regulation and different laws. As the DT system involves various specific city operating data, while urban safety and administration systems are distinct, it is harder to support other institutions' usage based on data demands, therefore, cross-institution and cross-region DT data framework is required for city information resource integration and fully visualized city operation process planning and management. However, for highly connected smart cities, high-tech reliance increases the concern about cybersecurity. Urban infrastructure O&M with DT applications face many challenges in the field of cybersecurity and regulation, such as citizens' personal data protection, regulations, policy clarification standards based on different categories of human behavior, and intelligent city models' access authority. It is also crucial for policymakers to consider the regulation tools and policies to promote city stakeholders' participation in smart city development and the daily O&M processes (Almeida, 2023).

4.2.3. Issues of information sharing and interoperability for DT application in project asset management

Towards the aim of realizing more efficient and comprehensive DT applications in project O&M, information and data are the primary elements, especially for empowering the interface between DT and multiple engineering technologies. As mentioned in previous sections, the data latency, accuracy, and source of historical data are all breakthroughs for DT applications in practice. The sensors' data transmission for DT system construction, the various sources of data integration with multiple technologies, the large amount of data empowerment, and interoperability problems would impact the coordination effects of these digital technologies. Collection of cyber-physical systems, VR/MR, Digital modelling, and IoT make it possible to upload data and knowledge for diagnosis tasks based on mega-data analysis. The whole process around data which indicates assets data collection, materials, and systems' compatibility is the core resource for the quality of DT function application. Therefore, the effective integration of the DT data model with the sensor data and its compatibility with the machinery equipment command reception system, the quality of the data, the data standards, and the restrictions on the level of authority between systems are all key factors in the O&M stage of the project.

Although previous studies have demonstrated HRC, it is the future of industrial production works, and any emerging technology must consider how to coordinate with humans and integrate with existing working processes and systems. One of the HRC difficulties is the dynamic nature of human behavior and the complexity of cognition is difficult to match perfectly with the need for data-driven adaptation (Malik and Brem, 2021). So, AI technology simulates the human behavior trajectory occupied one of the key commission and testing solutions (Wang et al., 2024), but it is imperative to create a framework or lead concept for industries to describe the technologies, structures, information flow, and processes that redefined operation methods. The risk assessment standard should be suitable for the HRC operational environment based on the new HRC safety standards. Wilhelm et al. (2021) mentioned that DT enables machines or robotics to concentrate on the safety of operators through integration with a VR environment in collaboration with a robotic arm to detect safety hazards and provide risk mitigation action immediately. The whole process is a two-way interaction and information exchange between the operator and the robot. Complex industrial environments and multiple operators' collaboration with the robotics and gesture evaluation is still challenging (Wang et al., 2024). DT is prone to realize interdisciplinary knowledge integration, however, the uniform convergence of application paradigms and process strategies is still fragmented (Fan et al., 2021).

4.2.4. Problems of blockchain integrated with DT in project O&M

To solve the data overwritten and reliability problem of DT, blockchain technology has been broadly discussed and trying to fix the data-related problem. Tavakoli et al. (2023) developed a DT data resource model based on the Remix Ethereum platform and Sepolia test network which enables asset model maintenance and real-time data acquisition in the dynamic O&M process. Blockchain reduces fraud activities and opportunism risks by accurately tracking asset information and data, which increases asset evaluation accuracy. However, the main problem is to test blockchain technology in real practice, promote suppliers' and stakeholders' understanding of this technology, and ensure strong data-synchronized with tele-infrastructure (Li et al., 2023).

In addition, because of the privacy nature of smart contracts and transaction data, cybersecurity and data protection problems should be given more attention when sharing information on blockchain platforms. Since most DT applications involve physical, optimized, simulated knowledge and technological models, intellectual property rights should be protected. Consequently, the regulation of blockchain technology and DT applications for commercial purposes should focus on the ethical consent and data monopoly problems associated with their development and implementation (Jiang et al., 2023). Clear regulation and governance rules for blockchain technology applications should be distinguished from other digital technologies, due to its decentralized transaction and algorithm-based trust mechanisms in the construction project supply chain management (Gai et al., 2022).

4.2.5. Project managers and operators' competence challenges of DT platforms alliance

The level of professional competence of system operators and the complexity of contextual information also pose challenges for multi-party collaboration. The characteristics of construction project stakeholders, cross-organizational collaboration, and temporary natures sometimes limit the digital transition acceptance. As such, complex project O&M tools like DT and AI need to develop a user-friendly dashboard in industrial practice. In addition, ease and knowledge understanding degree affect digital acceptance when using information and communication tools is the most significant factor. Project decisions would be directly impacted by changes in tool use. For example, the collaboration between various enterprises, their data and information analysis, processing capabilities, and compatibility differ. During the process of bidding, business plan evaluation, etc., herd decisions may occur. These decisions will impact various organizations and pose the greatest threat to rational decision-making (Shi et al., 2023). The decision maker's attention poses the biggest challenge to logical decision-making.

Researchers have discussed the success elements of how DT facilitates production and sustainability, but the critical factors of DT adaptation in the organization or operational procedure need further arguments (Deepu and Ravi, 2021). The key element of technology adoption is typically related to people who have the digital awareness and capability to conduct holistic implications and regular checks of the operational conditions. It requires high professional expertise for project managers to be equipped with the knowledge of organizational processes and O&M strategies, and the ability to provide a pivot and leadership role for digital transformation and DT adoption. This provides challenges for project management practitioners and advanced project management development. Especially, more and more emerging technologies have been implemented and explored in the construction industry, and this industry particularly depends on accurate events, risk, and cost budget control in project planning phase (Regona et al., 2022). High-end technologies like AI and DT utilized in the scheduling or O&M phases can reduce the time spent on repetitive tasks. Therefore, the project managers and experts establish a holistic digital environment and history data activation is still a daunting task.

Finally, the efficiency of project O&M costs and capital costs for introducing DT technologies will increase, but the investment performance and benefits are still unclear. These limitations hinder the implementation progress of DT, the whole planning, management, and procurement process of digital systems are meant to conform with the project's financial capabilities. The commercialization of DT is concerned with the market and industrial participants.

4.3. Future research studies of DT applications in project O&M

After the critical literature review, science mapping analysis, and qualitative discussion, the main research themes for DT in the project O&M have been identified. Notably, the identified mainstream research topics, research gaps, and future research directions are interlinked and progressive which can be shown in Figure 6. This section is based on the former two subsections' discussion to obtain the future domain research trends.

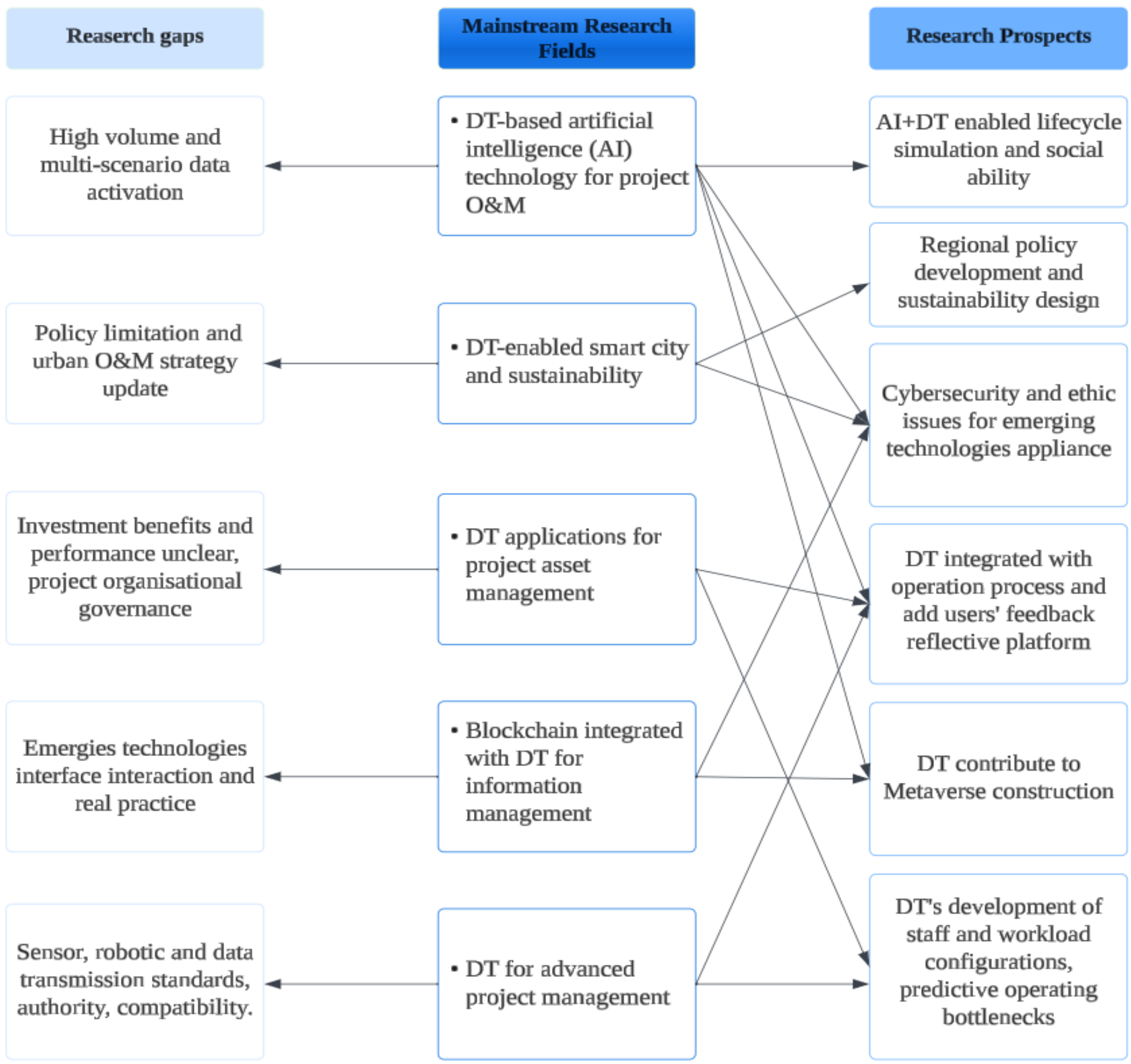

Fig. 6. Research framework showing the links between mainstream research fields, research gaps, and research prospects

1. **Smart City Scenario**. Smart city design, construction, and change cannot rely solely on industry-specific technology adoption and application. Regional policies can directly influence the state of smart city development, and the realization of smart cities relies not only on technology integration and consideration at the design stage but also on regional policy innovation (Hervás-Oliver, 2021), industry-related stakeholders, and expert participation. Smart city scenarios design and consideration can expand to the global perspectives, and reflect multi-attitudes of citizens, policymakers, and industries. Energy performance, intelligent agriculture, sustainability, etc. city development agenda will be considered first in DT simulation systems.
2. **Asset Data and information aggregation.** Project managers should improve their competence to comprehend and apply digital changes to organizational equipment and operating procedures. The operation of deploying predictive asset management models and the use of tools should consider the complexity of human involvement and behavior and mitigate the detrimental effect on rational decision-making in the name of efficiency. The integration of various technologies and apparatus throughout this time will unavoidably raise several issues that call for further debate, including system compatibility, the adaption of different machine interfaces, data fusion capabilities, and the best alignment of operational procedures. The investment efficiency on DT kinds of technologies should align with other digital technologies expenditure and their benefits for facilities management.
3. **AI and DT integration.** It is recommended to integrate data and systems of the whole construction ecosystem to establish a holistic project lifecycle and supply chain digital dynamic simulation. It is imperative to break the information island limitation and empower structural data. ML and deep learning technologies will be integrated with DT for human gestures and behavior prediction when collaborating with robotics (Wang et al., 2024). AI social ability development can predict human emotions, behavior, and thoughts, which will be utilized for risk, change, cost, quality, and contract management fields (Müller et al., 2024).
4. **Privacy and security.** Cybersecurity and regulations will be more robust and assisted by DT as a reference when designing, commissioning, executing, and terminating policies or

industrial regulations. Ethical consideration and personal data protection measures will also be integrated into DT and other emerging technologies development.

5. **O&M Scenario Consideration.** DT encourages the revitalization of information management, but more research is needed to understand how data information can be used to enhance physical workflow and staffing, identify operational and maintenance bottlenecks, plan staff workloads, and apply employee data and job matching in smart ways.
6. **Decision-making Support.** In the future, the decision-making optimization will be enriched because of the incorporation of users' feedback on DT and the feedback platform in DT to assure resource delivery and facilitate the interaction between the virtual world, physical world, and human's social world (Rožanec et al., 2022). DT and blockchain technologies will contribute to the metaverse construction.

5. Conclusions

This review paper applied a scientometric analysis method which consists of a literature search, literature selection, science mapping analysis, and a qualitative discussion based on 444 published articles related to DT applications in project O&M. It was found that the number of published articles in the studied domain significantly increased from 2020, indicating that the attention paid to DT applications in project O&M from researcher and practitioners. Besides, there were 78 relevant peer-reviewed journals selected, finding that *Automation in Construction, Journal of Manufacturing Systems,* and *International Journal of Computer Integrated Manufacturing* contributed to the largest number (i.e., 11.71%) of published articles. Subsequently, the author's keywords in DT applications in project O&M were identified by keyword co-occurrence analysis, which includes BIM, human-robotic collaboration, and model-based system engineering. Some keywords are related to basic technology utilization in new scenarios research like smart city, smart manufacturing, and modular construction. Other emerging technology topics are still popular like AI, blockchain technology, sensors, BIM, etc. These results suggest that experts concentrate more on information integration issues because emerging technology can strongly change and facilitate information management methods. In addition, it was found from the document analysis that the most often referenced articles combining DT with other emerging technologies—such as reinforcement learning, deep learning, transfer learning, and ML—remain a key area for enhancing the time latency and data accuracy problems of DT, as well as provided as a simulation model training platform.

For the qualitative discussion, mainstream research topics, research gaps, and future research trends and challenges of DT application in project O&M were identified. The mainstream research topics include (1) DT-based artificial intelligence (AI) technology for project O&M, (2) DT-enabled smart city and sustainability, (3) DT applications for project asset management, (4) Blockchain-integrated DT for project O&M, and (5) DT for advanced project management. Based on the identified mainstream research topics, the research gaps and future research directions were discussed. Lastly, a research framework was proposed based on linking the mainstream topics, research gaps, and future research trends. Research into the application of DT to the construction sector is of utmost importance because of the wide range of stakeholders, significant amount of capital, lengthy operation and maintenance cycles, and the influence of construction hazards. This study contributes to identifying significant journals, areas, and publications that have dealt with connected subjects, adding to the body of knowledge and potential future research directions for the application of DT in the construction sector.

6. Limitations and future research works

There are several limitations of this review study. First, the number of available articles pertinent to the studied topic is not enough, and the topic is comparatively new, which causes the scientometric analysis not to have an adequate sample size, and the total link strength of most articles was too short which affected the influential research of authors, articles, journals, countries/regions. Second, detailed technical analyses of specific emerging technologies in O&M scenarios are lacking, providing only an overall theoretical framework and view of operations for the phase. Third, the collection of articles ends in January 2024 from the Scopus database, and the selection of the articles was limited to only English, thus, journal articles in other languages were excluded. These exclusion criteria could cause a decline in annual publishing numbers and trend graphs starting in 2024. Consequently, time restrictions are most likely to affect this phenomenon. However, the detailed qualitative discussion combined with the science mapping analysis supported by the existing insights and opinions by measurement analysis which increase the science and reliability of a regular literature review.

To address the limitations, future studies should include more in-depth explanations of the significance of new technologies related to DT systems for project O&M, along with illustrative examples. Next, incorporating specific case studies would have improved the technical explanations' realism and concreteness, making them simpler to comprehend and accept. In addition, project managers must update their digital expertise and assist the DT technology to realize staff career and job information management, workforce, and other resource deployments. Moreover, standards for security assurance and standardized information communication practices should also be provided by the integration and configuration of various technologies. Furthermore, the advantages of DT for project O&M still require development with government policy support, broad industry acceptance, and company adoption capacity. Lastly, to increase the sample size of the included articles, further studies should include articles published in other languages and databases.

Data availability statement

The datasets used in this study are available from the corresponding author upon request.

Declaration of competing interest

None

References

Adu-Amankwa, N. A. N., Rahimian, F. P., Dawood, N. and Park, C. (2023), "Digital Twins and Blockchain technologies for building lifecycle management", *Automation in Construction,* Vol. 155, pp. 105064, doi: https://doi.org/10.1016/j.autcon.2023.105064.

Agnusdei, G. P., Elia, V. and Gnoni, M. G. (2021), "Is digital twin technology supporting safety management? A bibliometric and systematic review", *Applied Sciences,* Vol. 11, No. 6, pp. 2767, doi: https://doi.org/10.3390/app11062767.

Almeida, F. (2023), "Prospects of Cybersecurity in Smart Cities" *Future Internet,* Vol. 15, No. 9, pp. 285, doi: https://doi.org/10.3390/fi15090285.

Antwi-Afari, M. F., Li, H., Chan, A. H. S., Seo, J., Anwer, S., Mi, H.-Y., Wu, Z. and Wong, A. Y. L. (2023), "A science mapping-based review of work-related musculoskeletal disorders among construction workers", *Journal of safety research,* Vol. 85, pp. 114-128, doi: https://doi.org/10.1016/j.jsr.2023.01.011.

Aheleroff, S., Xu, X., Zhong, R.Y., Lu, Y., 2021. Digital twin as a service (DTaaS) in industry 4.0: An architecture reference model. *Advanced Engineering Informatics*, Vol. 47, pp. 101225, doi: https://doi.org/10.1016/j.aei.2020.101225.

Baratta, A., Cimino, A., Longo, F. & Nicoletti, L. 2023. Digital Twin for Human-Robot Collaboration enhancement in manufacturing systems: literature review and direction for future developments. *Computers & Industrial Engineering*, Vol. 107, pp. 109764, doi: https://doi.org/10.1016/j.cie.2023.109764.

Boje, C., Guerriero, A., Kubicki, S. & Rezgui, Y. 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in construction,* Vol. 114, pp. 103179, doi: https://doi.org/10.1016/j.autcon.2020.103179.

Bordegoni, M. & Ferrise, F. 2023. Exploring the intersection of metaverse, digital twins, and artificial intelligence in training and maintenance. *Journal of Computing and Information Science in Engineering,* Vol. 23**,** pp. 060806, doi: https://doi.org/10.1115/1.4062455.

Broo, D. G. & Schooling, J. 2023. Digital twins in infrastructure: definitions, current practices, challenges and strategies. *International Journal of Construction Management,* Vol. 23**,** pp. 1254-1263, doi: https://doi.org/10.1080/15623599.2021.1966980.

Bujari, A., Calvio, A., Foschini, L., Sabbioni, A. & Corradi, A. 2021. A digital twin decision support system for the urban facility management process. *Sensors,* Vol. 21**,** pp. 8460, doi: https://doi.org/10.3390/s21248460.

Booyse, W., Wilke, D.N., Heyns, S., 2020. Deep digital twins for detection, diagnostics and prognostics. *Mechanical Systems and Signal Processing*, Vol. 140, pp. 106612, doi: https://doi.org/10.1016/j.ymssp.2019.106612.

Chen, D., Xiang, P. & Jia, F. 2022. Performance measurement of operation and maintenance for infrastructure mega-project based on entropy method and DS evidence theory. *Ain Shams Engineering Journal,* Vol. 13**,** pp. 101591, doi: https://doi.org/10.1016/j.asej.2021.09.018.

Choi, S. H., Park, K.-B., Roh, D. H., Lee, J. Y., Mohammed, M., Ghasemi, Y. & Jeong, H. 2022. An integrated mixed reality system for safety-aware human-robot collaboration using deep learning and digital twin generation. *Robotics and Computer-Integrated Manufacturing,* Vol. 73**,** pp. 102258, doi: https://doi.org/10.1016/j.rcim.2021.102258.

Deloitte insights (2020). *The kinetic leader: Boldly reinventing the enterprise***.** Available at: https://www2.deloitte.com/ch/en/pages/technology/articles/the-kinetic-leader-boldly-reinventing-the-enterprise.html (Accessed: 12 January 2024)

Deloitte insights (2021). *The worker-employer relationship disrupted.* Available at: https://www2.deloitte.com/us/en/insights/focus/human-capital-trends/2021/the-evolving-employer-employee-relationship.html (Accessed: 12 January 2024)

D'urso, D., Chiacchio, F., Cavalieri, S., Gambadoro, S. & Khodayee, S. M. 2024. Predictive maintenance of standalone steel industrial components powered by a dynamic reliability digital twin model with artificial intelligence. *Reliability Engineering & System Safety,* Vol. 243**,** pp. 109859, doi: https://doi.org/10.1016/j.ress.2023.109859.

Dabirian, S., Saad, M. M., Hussain, S., Peyman, S., Rahimi, N., Monsalvete Alvarez U, P., Yefi, P. & Eicker, U. 2023. Structuring heterogeneous urban data: A framework to develop the data model for energy simulation of cities. *Energy and buildings,* Vol. 296**,** pp. 113376, doi: https://doi.org/10.1016/j.enbuild.2023.113376.

Deebak, B. D. & Al-Turjman, F. 2022. Digital-twin assisted: Fault diagnosis using deep transfer learning for machining tool condition. *International Journal of Intelligent Systems,* Vol. 37**,** pp. 10289-10316, doi: https://doi.org/10.1002/int.22493.

Deepu, T. & Ravi, V. 2021. Exploring critical success factors influencing adoption of digital twin and physical internet in electronics industry using grey-DEMATEL approach. *Digital Business,* Vol. 1**,** pp. 100009, doi: https://doi.org/10.1016/j.digbus.2021.100009.

Dreyer, M., Nicolet, C., Gaspoz, A., Gonçalves, N., Rey-Mermet, S. & Boulicaut, B. Monitoring 4.0 of penstocks: digital twin for fatigue assessment. IOP Conference Series: Earth and Environmental Science, Vol. 774, No. 1, pp. 012009, doi: https://doi.org/10.1088/1755-1315/774/1/012009

Edwards, C., Morales, D. L., Haas, C., Narasimhan, S. & Cascante, G. 2023. Digital twin development through auto-linking to manage legacy assets in nuclear power plants. *Automation in Construction,* Vol. 148**,** pp. 104774, doi: https://doi.org/10.1016/j.autcon.2023.104774.

Fang, Z., Jiang, F., Yan, J., Lu, Q., Chen, L., Tang, J., Hong, J. & Broyd, T. 2024. A novel lightweight CF decision-making approach for highway reconstruction and operation. *Journal of Cleaner Production*, Vol. 434, pp. 140127, doi: https://doi.org/10.1016/j.jclepro.2023.140127.

Feng, K., Ji, J., Zhang, Y., Ni, Q., Liu, Z. & Beer, M. 2023. Digital twin-driven intelligent assessment of gear surface degradation. *Mechanical Systems and Signal Processing,* Vol. 186, pp. 109896, doi: https://doi.org/10.1016/j.ymssp.2022.109896.

Gai, K., Zhang, Y., Qiu, M. & Thuraisingham, B. 2022. Blockchain-enabled service optimizations in supply chain digital twin. *IEEE Transactions on Services Computing*, Vol. 16, No. 3, pp. 1673–1685. doi: https://doi.org/10.1109/TSC.2022.3192166.

Gao, Y., Li, H., Xiong, G. & Song, H. 2023. AIoT-informed digital twin communication for bridge maintenance. *Automation in Construction,* Vol. 150, pp. 104835, doi: https://doi.org/10.1016/j.autcon.2023.104835.

Ghansah, F. A., & Lu, W. 2024. Major opportunities of digital twins for smart buildings: a scientometric and content analysis. *Smart and Sustainable Built Environment*, Vol. 13, No.1, pp. 63-84, doi: https://doi.org/10.1108/SASBE-09-2022-0192.

Goyal, L. K., Chauhan, R., Kumar, R. & Rai, H. S. 2020. Use of BIM in Development of Smart Cities: A Review. *IOP Conference Series: Materials Science and Engineering,* Vol. 955, pp. 012010, doi: https://doi.org/10.1088/1757-899X/955/1/012010.

Grüner, S., Hoernicke, M., Stark, K., Schoch, N., Eskandani, N. & Pretlove, J. 2023. Towards asset administration shell-based continuous engineering in process industries. *at-Automatisierungstechnik,* Vol. 71, No. 8, pp. 689-708, doi: https://doi.org/10.1515/auto-2023-0012.

Harzing, A.-W. & Alakangas, S. 2016. Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison. *Scientometrics*, Vol. 106, No. 2, pp. 787-804, doi: https://doi.org/10.1007/s11192-015-1798-9.

He, R., Li, M., Gan, V.J., Ma, J., 2021. BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study. Journal of Cleaner Production, Vol. 278, pp. 123505, doi: https://doi.org/10.1016/j.jclepro.2020.123505.

Jain, S. & Narayanan, A. 2023. Digital Twin–Enabled Machine Learning for Smart Manufacturing. *Smart and Sustainable Manufacturing Systems,* Vol. 7, No. 1, pp. 111-128, doi: https://doi.org/10.1520/ssms20220035.

Jiang, Y. 2021. Intelligent building construction management based on BIM digital twin. *Computational Intelligence and Neuroscience,* Vol. 2021, pp. 1–11, doi: https://doi.org/10.1155/2021/4979249.

Jiang, Y., Liu, X., Wang, Z., Li, M., Zhong, R. Y. & Huang, G. Q. 2023. Blockchain-enabled digital twin collaboration platform for fit-out operations in modular integrated construction. *Automation in Construction,* Vol. 148, pp. 104747, doi: https://doi.org/10.1016/j.autcon.2023.104747.

Jiang, Z., Guo, Y. & Wang, Z. 2021. Digital twin to improve the virtual-real integration of industrial IoT. *Journal of Industrial Information Integration,* Vol. 22, pp. 100196, doi: https://doi.org/10.1016/j.jii.2020.100196.

Kaewunruen, S. & Lian, Q. 2019. Digital twin aided sustainability-based lifecycle management for railway turnout systems. *Journal of Cleaner Production,* Vol. 228, pp. 1537-1551, doi: https://doi.org/10.1016/j.jclepro.2019.04.156.

Kamari, M. & Ham, Y. 2022. AI-based risk assessment for construction site disaster preparedness through deep learning-based digital twinning. *Automation in Construction,* Vol. 134, pp. 104091, doi: https://doi.org/10.1016/j.autcon.2021.104091.

Keskin, B., Salman, B. & Koseoglu, O. 2022. Architecting a BIM-based digital twin platform for airport asset management: a model-based system engineering with SysML approach. *Journal of*

Construction Engineering and Management, Vol. 148, pp. 04022020, doi: https://doi.org/10.1061/(ASCE)CO.1943-7862.000227.
Kumar, A. & Choukimath, P. A. 2015. Popular scientometric analysis, mapping and visualisation softwares: An overview. ISBN: 978-93-81232-05-7, doi: https://doi.org/10.1504/ijhvs.2018.094829.
Lee, D., Lee, S. H., Masoud, N., Krishnan, M. & Li, V. C. 2021. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in construction,* Vol. 127, pp. 103688, doi: https://doi.org/10.1016/j.autcon.2021.103688.
Li, M., Fu, Y., Chen, Q. & Qu, T. 2023. Blockchain-enabled digital twin collaboration platform for heterogeneous socialized manufacturing resource management. *International Journal of Production Research,* Vol. 61, No. 12, pp. 3963-3983, doi: https://doi.org/10.1080/00207543.2021.1966118.
Li, L., Lei, B., Mao, C., 2022. Digital twin in smart manufacturing. *Journal of Industrial Information Integration*, Vol. 26, pp. 100289, doi: https://doi.org/10.1016/j.jii.2021.100289.
Liu, Q., Zhang, H., Leng, J., Chen, X., 2019. Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. *International Journal of Production Research*, Vol. 57, No.12, pp. 3903–3919, https://doi.org/10.1080/00207543.2018.1471243.
Long, W., Bao, Z., Chen, K., Ng, S. T., & Wuni, I. Y. 2024. Developing an integrative framework for digital twin applications in the building construction industry: A systematic literature review. *Advanced Engineering Informatics*, Vol. 59, pp. 102346, doi: https://doi.org/10.1016/j.aei.2023.102346.
Love, P. E. & Matthews, J. 2019. The 'how'of benefits management for digital technology: From engineering to asset management. *Automation in Construction,* Vol. 107, pp. 102930, doi: https://doi.org/10.1016/j.autcon.2019.102930.
Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J. & Schooling, J. 2020a. Developing a digital twin at building and city levels: Case study of West Cambridge campus. *Journal of Management in Engineering,* Vol. 36, No. 3, pp. 05020004, doi: https://doi.org/10.1061/(asce)me.1943-5479.0000763.
Lu, Q., Xie, X., Parlikad, A. K. & Schooling, J. M. 2020b. Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation in Construction,* Vol. 118, pp. 103277, doi: https://doi.org/10.1016/j.autcon.2020.103277.
Lv, Z. & Xie, S. 2022. Artificial intelligence in the digital twins: State of the art, challenges, and future research topics. *Digital Twin,* Vol. 1, pp. 12, doi: https://doi.org/10.12688/digitaltwin.17524.1.
Luo, W., Hu, T., Ye, Y., Zhang, C., Wei, Y., 2020. A hybrid predictive maintenance approach for CNC machine tool driven by Digital Twin. *Robotics and Computer-Integrated Manufacturing,* Vol. 65, pp. 101974, doi: https://doi.org/10.1016/j.rcim.2020.101974.
Malik, A. A. & Brem, A. 2021. Digital twins for collaborative robots: A case study in human-robot interaction. *Robotics and Computer-Integrated Manufacturing,* Vol. 68, pp. 102092, doi: https://doi.org/10.1016/j.rcim.2020.102092.
Michie, S., Thomas, J., Johnston, M., Aonghusa, P. M., Shawe-Taylor, J., Kelly, M. P., Deleris, L. A., Finnerty, A. N., Marques, M. M. & Norris, E. 2017. The Human Behaviour-Change Project: harnessing the power of artificial intelligence and machine learning for evidence synthesis and interpretation. *Implementation Science,* Vol. 12, No.1, pp.112, doi: https://doi.org/10.1186/s13012-017-0641-5.
Mongeon, P. & Paul-Hus, A. 2016. The journal coverage of Web of Science and Scopus: a comparative analysis. *Scientometrics,* Vol. 106, No. 1, pp. 213-228, doi: https://doi.org/10.1007/s11192-015-1765-5.
Müller-Zhang, Z., Kuhn, T. & Antonino, P. O. 2023. Towards live decision-making for service-based production: Integrated process planning and scheduling with Digital Twins and Deep-Q-Learning.

Computers in Industry, Vol. 149, pp. 103933, doi: https://doi.org/10.1016/j.compind.2023.103933.

Müller, R., Locatelli, G., Holzmann, V., Nilsson, M. & Sagay, T. 2024. Artificial Intelligence and Project Management: Empirical Overview, State of the Art, and Guidelines for Future Research. *Project Management Journal,* Vol. 55, pp. 5-19, doi: https://doi.org/10.1177/87569728231225198.

Opoku, D.-G. J., Perera, S., Osei-Kyei, R. & Rashidi, M. 2021. Digital twin application in the construction industry: A literature review. *Journal of Building Engineering,* Vol. 40**,** pp. 102726, doi: https://doi.org/10.1016/j.jobe.2021.102726.

Pan, Y., Qu, T., Wu, N., Khalgui, M. & Huang, G. 2021. Digital twin based real-time production logistics synchronization system in a multi-level computing architecture. *Journal of Manufacturing Systems,* Vol. 58**,** pp. 246-260, doi: https://doi.org/10.1016/j.jmsy.2020.10.015.

Pan, Y. & Zhang, L. 2021. A BIM-data mining integrated digital twin framework for advanced project management. *Automation in Construction,* Vol. 124**,** pp. 103564, doi: https://doi.org/10.1016/j.autcon.2021.103564.

Park, K.T., Son, Y.H., Noh, S.D., 2021. The architectural framework of a cyber physical logistics system for digital-twin-based supply chain control. *International Journal of Production Research,* Vol. 59, pp. 5721–5742, doi: https://doi.org/10.1080/00207543.2020.1788738.

Papadonikolaki, E. & Jaskula, K. 2023. 35. Taming complexity in project organising through blockchain. *Research Handbook on Complex Project Organizing***,** pp. 353, ISBN: 978-1-80088-028-3.

Popović, M. & Rajović, B. 2021. Impact of the Industry 4.0 on smart city development. *Journal of Engineering Management and Competitiveness (JEMC),* Vol. 11, pp. 64-76, doi: https://doi.org/10.5937/jemc2101064p.

Qian, X. & Papadonikolaki, E. 2021. Shifting trust in construction supply chains through blockchain technology. *Engineering, Construction and Architectural Management,* Vol. 28**,** pp. 584-602, doi: https://doi.org/10.1108/ecam-12-2019-0676.

Radanliev, P., De Roure, D., Nicolescu, R., Huth, M. & Santos, O. 2022. Digital twins: Artificial intelligence and the IoT cyber-physical systems in Industry 4.0. *International Journal of Intelligent Robotics and Applications,* Vol. 6, No.1, pp. 171-185, doi: https://doi.org/10.1007/s41315-021-00180-5.

Radzi, A. R., Azmi, N. F., Kamaruzzaman, S. N., Rahman, R. A. & Papadonikolaki, E. 2024. Relationship between digital twin and building information modeling: a systematic review and future directions. *Construction Innovation,* Vol. 24, No. 3, pp. 811-829, doi: https://doi.org/10.1108/ci-07-2022-0183.

Ramonell, C., Chacón, R. & Posada, H. 2023. Knowledge graph-based data integration system for digital twins of built assets. *Automation in Construction,* Vol. 156**,** pp. 105109, doi: https://doi.org/10.1016/j.autcon.2023.105109.

Regona, M., Yigitcanlar, T., Xia, B. & Li, R. Y. M. 2022. Opportunities and adoption challenges of AI in the construction industry: a PRISMA review. *Journal of Open Innovation: Technology, Market, and Complexity,* Vol. 8**,** No. 1, pp. 45, doi: https://doi.org/10.3390/joitmc8010045.

Rožanec, J. M., Lu, J., Rupnik, J., Škrjanc, M., Mladenić, D., Fortuna, B., Zheng, X. & Kiritsis, D. 2022. Actionable cognitive twins for decision making in manufacturing. *International journal of production research,* Vol. 60**,** No. 2, pp. 452-478, doi: https://doi.org/10.1080/00207543.2021.2002967.

Safiullin, A., Krasnyuk, L. & Kapelyuk, Z. Integration of Industry 4.0 technologies for "smart cities" development. IOP conference series: materials science and engineering, Vol. 497, No. 1, pp. 012089, doi: https://doi.org/10.1088/1757-899X/497/1/012089.

Semeraro, F., Griffiths, A. & Cangelosi, A. 2023. Human–robot collaboration and machine learning: A systematic review of recent research. *Robotics and Computer-Integrated Manufacturing,* Vol. 79**,** pp. 102432, doi: https://doi.org/10.1016/j.rcim.2022.102432.

Shi, J., Dourthe, L., Li, D., Deng, L., Louback, L., Song, F., Abolins, N., Verano, F., Zhang, P. & Groover, J. 2023. Real-Time Underreamer Vibration Predicting, Monitoring, and Decision-Making Using Hybrid Modeling and a Process Digital Twin. *SPE Drilling & Completion,* Vol. 38**,** No. 2, pp. 201-219, doi: https://doi.org/10.2118/208795-pa.

Sun, X., Chen, W., Xiong, X., Chen, W. & Jin, Y. 2022. A Variable Configuration Force Sensor with Adjustable Resolution for Robotic Applications. *IEEE Transactions on Industrial Electronics,* Vol. 70, No.2, pp. 2066-2075, doi: https://doi.org/10.1109/tie.2022.3163538.

Stark, R., Fresemann, C., Lindow, K., 2019. Development and operation of Digital Twins for technical systems and services. *CIRP Annal*, Vol. 68, pp. 129–132, doi: https://doi.org/10.1016/j.cirp.2019.04.024.

Silva, B.N., Khan, M., Han, K., 2018. Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities. *Sustainable Cities and Society*, Vol. 38, pp. 697–713, doi: https://doi.org/10.1016/j.scs.2018.01.053.

Tavakoli, P., Yitmen, I., Sadri, H. & Taheri, A. 2023. Blockchain-based digital twin data provenance for predictive asset management in building facilities. *Smart and Sustainable Built Environment*, Vol. 13, No. 1, pp. 4–21, doi: https://doi.org/10.1108/SASBE-07-2023-0169.

Tomičić Pupek, K., Pihir, I. & Tomičić Furjan, M. 2019. Smart city initiatives in the context of digital transformation–scope, services and technologies. *Management: journal of contemporary management issues,* Vol. 24**,** No. 1, pp. 39-54, doi: https://doi.org/10.30924/mjcmi.24.1.3.

Tao, F., Zhang, M., Liu, Y., Nee, A.Y.C., 2018. Digital twin driven prognostics and health management for complex equipment. CIRP Annal, Vol. 67, pp.169–172, doi: https://doi.org/10.1016/j.cirp.2018.04.055.

Van Eck, N. & Waltman, L. 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. *scientometrics,* Vol. 84**,** No. 2, pp. 523-538, doi: https://doi.org/10.1007/s11192-009-0146-3.

Van Eck, N. J. & Waltman, L. 2017. Citation-based clustering of publications using CitNetExplorer and VOSviewer. *Scientometrics,* Vol. 111**,** No. 2, pp. 1053-1070, doi: https://doi.org/10.1007/s11192-017-2300-7.

Wang, S., Zhang, J., Wang, P., Law, J., Calinescu, R. & Mihaylova, L. 2024. A deep learning-enhanced Digital Twin framework for improving safety and reliability in human–robot collaborative manufacturing. *Robotics and computer-integrated manufacturing,* Vol. 85**,** pp. 102608, doi: https://doi.org/10.1016/j.rcim.2023.102608.

Wang, W., Zaheer, Q., Qiu, S., Wang, W., Ai, C., Wang, J., Wang, S. & Hu, W. 2023. Digital Twins in Operation and Maintenance (O&P). *Digital Twin Technologies in Transportation Infrastructure Management,* pp. 179-203, ISBN: 978-981-9958-04-7, doi: https://doi.org/10.1007/978-981-99-5804-7_6.

Wang, Q., Jiao, W., Wang, P., Zhang, Y., 2021. Digital twin for human-robot interactive welding and welder behavior analysis. *IEEE/CAA Journal of Automatica Sinica*, Vol. 8, No. 2, pp. 334–343, doi: https://doi.org/10.1109/jas.2020.1003518.

Wetzel, E. M. & Thabet, W. Y. 2015. The use of a BIM-based framework to support safe facility management processes. *Automation in Construction,* Vol. 60**,** pp. 12-24, doi: https://doi.org/10.1016/j.autcon.2015.09.004.

Wilhelm, J., Petzoldt, C., Beinke, T. & Freitag, M. 2021. Review of digital twin-based interaction in smart manufacturing: Enabling cyber-physical systems for human-machine interaction. *International Journal of Computer Integrated Manufacturing,* Vol. 34, pp. 1031-1048, doi: https://doi.org/10.1080/0951192X.2021.1963482.

Wu, S., Hou, L., Zhang, G. K. & Chen, H. 2022. Real-time mixed reality-based visual warning for construction workforce safety. *Automation in Construction,* Vol. 139, pp. 104252, doi: https://doi.org/10.1016/j.autcon.2022.104252.

Wu, Z., Yang, K., Lai, X. & Antwi-Afari, M. F. 2020. A scientometric review of system dynamics applications in construction management research. *Sustainability,* Vol. 12, No. 18, pp. 7474, doi: https://doi.org/10.3390/su12187474.

Xia, Q., Yue, J., Chen, J., Cui, Z. & Lyu, F. 2023. Early fault diagnosis for DC/DC converters based on digital twins and transfer learning. *Measurement Science and Technology,* Vol. 34, No. 11, pp. 115008, doi: https://doi.org/10.1088/1361-6501/ace987.

Xia, H., Liu, Z., Efremochkina, M., Liu, X., Lin, C., 2022. Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration. *Sustainable Cities and Society*, Vol. 84, pp. 104009, doi: https://doi.org/10.1016/j.scs.2022.104009.

Xiong, M., Wang, H., Fu, Q. & Xu, Y. 2021. Digital twin–driven aero-engine intelligent predictive maintenance. *The International Journal of Advanced Manufacturing Technology,* Vol. 114, No. 11, pp. 3751-3761, doi: https://doi.org/10.1007/s00170-021-06976-w.

Ye, Z., Antwi-Afari, M. F., Tezel, A., & Manu, P. (2024). Building information modeling (BIM) in project management: A bibliometric and science mapping review. *Engineering, Construction and Architectural Management*, ISSN: 0969-9988, doi: https://doi.org/10.1108/ECAM-04-2023-0355.

Yevu, S. K., Owusu, E. K., Chan, A. P., Sepasgozar, S. M., & Kamat, V. R. 2023. Digital twin-enabled prefabrication supply chain for smart construction and carbon emissions evaluation in building projects. *Journal of Building Engineering*, Vol. 78, pp. 107598, doi: https://doi.org/10.1016/j.jobe.2023.107598.

Zhang, A., Yang, J. & Wang, F. 2023a. Application and enabling technologies of digital twin in operation and maintenance stage of the AEC industry: A literature review. *Journal of Building Engineering***,** Vol. 80, pp. 107859, doi: https://doi.org/10.1016/j.jobe.2023.107859.

Zhang, H., Zhou, Y., Zhu, H., Sumarac, D. & Cao, M. 2021. Digital twin-driven intelligent construction: features and trends. *Structural Durability & Health Monitoring,* Vol. 15, No. 3, pp. 183–206, doi: https://doi.org/10.32604/sdhm.2021.018247.

Zhang, J., Chan, C. C., Kwok, H. H. & Cheng, J. C. 2023b. Multi-indicator adaptive HVAC control system for low-energy indoor air quality management of heritage building preservation. *Building and Environment,* Vol. 246**,** pp. 110910, doi: https://doi.org/10.1016/j.buildenv.2023.110910.

Zhang, L., Guo, J., Fu, X., Tiong, R. L. K. & Zhang, P. 2024. Digital twin enabled real-time advanced control of TBM operation using deep learning methods. *Automation in Construction,* Vol. 158**,** pp. 105240, doi: https://doi.org/10.1016/j.autcon.2023.105240.

Zhang, Y., Fang, L., Qi, Z. & Deng, H. 2023c. A Review of Remaining Useful Life Prediction Approaches for Mechanical Equipment. *IEEE Sensors Journal*, Vol. 23, No. 24, pp. 29991–30006, doi: https://doi.org/10.1109/JSEN.2023.3326487

Zhao, J., Feng, H., Chen, Q. & De Soto, B. G. 2022. Developing a conceptual framework for the application of digital twin technologies to revamp building operation and maintenance processes. *Journal of Building Engineering,* Vol. 49, pp. 104028, doi: https://doi.org/10.1016/j.jobe.2022.104028.

Zhu, F., Lv, Y., Chen, Y., Wang, X., Xiong, G. & Wang, F.-Y. 2019. Parallel transportation systems: Toward IoT-enabled smart urban traffic control and management. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 21, No. 10, pp. 4063-4071, doi: https://doi.org/10.1109/tits.2019.2934991.

Zhu, Q., Zhou, T., Xia, P. & Du, J. 2022. Robot Planning for Active Collision Avoidance in Modular Construction: Pipe Skids Example. *Journal of Construction Engineering and Management,* Vol. 148, No. 10, pp. 04022114, doi: https://doi.org/10.1061/(asce)co.1943-7862.0002374.