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) industry. Although numerous articles are pertinent to DT applications, existing research areas and potential future 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 – 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 summarizing 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 whilst data from engineering assets and systems are essential for equipment monitoring and diagnostics (Shi et al., 2023). The use of data can influence decision-making across the project management life cycle. This is 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) (Keogh and Smallwood, 2021). Deloitte Insight (2021) suggested that over 70% of respondents expressed that their organizations are utilizing artificial intelligence (AI). Results from more than 90% of chief information officers and senior technology directors indicated that data analytics and cognition would have the second-largest influence on enterprises in the next three years (Deloitte Insight, 2020). Therefore, the construction industry should primarily focus on smart project asset management in the 4IR era.

Project operation and maintenance (O&M) phase has lasted for more than several decades, making it difficult to implement smart construction technologies (Wang et al., 2023). All construction project's costs include a sizeable portion of the O&M phase. Data and digital information are essential for daily construction management and equipment maintenance of projects. One of the biggest challenges of project O&M management is maintaining the integrity, validity, and inter/intra-relationships of data (Wetzel and Thabet, 2015). It is reported that the construction industry contributes to nearly 10% of gross domestic product (GDP) in different countries whilst the digital twin (DT) has been utilized in many countries such as China, Australia, United States, and United Kingdom (Opoku et al., 2021). Hence, the application of DT in construction project O&M plays a significant role in future sector development, occupational optimization, and work process improvement (Feng et al., 2023).

Meanwhile, DT as a 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 cycle and physical detecting mechanisms (Chen et al., 2022). They optimized the procedure through accurate calculation to save cost, but this method lacks consideration for strategy limitation and the relationship of applicants' configuration. As the computing 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 enhance 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. 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, and health status testing. 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) industry is undergoing a bourgeoning digital transformation, data virtualization technologies and representation levels have become a new and critical research direction (D'Urso et al., 2024). Opoku et al. (2021) analyzed the application of DT in several areas such as facility management, logistics management, monitoring and control, and structural interaction in the project lifecycle. These areas 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 protocol for data standards and monitoring to increase the added value of equipment data. Meanwhile 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 its 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 January 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 research 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/construction 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 internet of things (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 summarizes 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 analyze and virtualize related articles on DT applications in project O&M. This method provides an in-depth understanding, structure, knowledge integration, and research trends (e.g., author, keywords, documents, etc.) between different domains (Shi and Antwi-Afari, 2023; Zhang et al., 2024). The Scopus database was used to search for relevant publications and serves as a source of data collection. A systematic review was conducted to synthesize the recent and existing research studies. This approach of reviewing existing literature is transparent, reliable, and minimizes bias (Rethlefsen et al., 2021). 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.

<Please insert Figure 1 about here>

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 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; Chiang et al., 2023), thus, it was selected for the present review study. A thorough search was carried out using a two-part search string in the "article title/abstract/keyword" field. The first search string of keywords includes "digital twin" OR "digital twins" OR "virtual counterpart" OR "digital replica" OR "virtual twin", while the second search string 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, 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 was limited to "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, whilst 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 DT applications in project O&M were removed. Meanwhile, other articles without digital object identifier (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.

<Please insert Table 1 about here>

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 creates 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 emerging keywords, while document analysis displays the number of citations of documents (Van Eck and Waltman, 2010). These results were further used to understand and discuss the mainstream research topics, research gaps and future research directions of DT in project O&M.

2.4. Stage 4: Qualitative discussion

This stage analyzes the contents of key selected articles whose objectives and findings were thoroughly assessed and aligned with this study's goals such as the mainstream research topics, research gaps, and future research directions in the field of DT in project O&M. The results were obtained and based on the relevant publications, data visualization, and temporal classification. Meanwhile, the document and keyword analyses revealed the hot topics and research trends of DT applications in project O&M. The goal of assessing DT usage in the construction sector and establishing practical applications in project O&M is to highlight the research problems so that other researchers and professionals may use them to guide future development directions. 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 the 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 of 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. Future research should confirm whether the speculation is correct.

<Please insert Figure 2 about here>

3.2. Selection of relevant peer-reviewed journals

After manual screening, 444 articles related to DT in project O&M were selected and analyzed through 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 (i.e., 23 articles), accounting for 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.

<Please insert Table 2 about here>

3.3. Keyword co-occurrence analysis

Keywords are representative and refined expressions of the content of a research article. Keyword co-occurrence analysis can identify hot topics and research areas in the knowledge domain over a specific period. In VOSviewer, the co-occurrence of keyword analysis was based on 444 articles. The author keyword indicates the keyword provided by the author. The distance between two nodes represents the strength of the relationship between them. The farther 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 1,582 keywords, 35 items met the criteria when the minimum number of occurrences was set at 4. This threshold was chosen after several attempts were made to obtain the best clusters of keywords. 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 keywords. Additionally, certain keywords had relatively high total link strength scores, which indicate a stronger connection between the keywords, topics, and themes. The top five total link strength scores include, "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 results also indicate that they are popular topics in DT in project O&M during the studied period.

<Please insert Figure 3 about here>

Table 3 summarizes 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 that these keywords are widely associated and analyzed in DT in project O&M research. 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, "cyber-physical systems", "cloud computing", and "service-oriented architecture" were prevalent keywords in 2020. Then, 4 keywords related to the function of DT, such as "simulation", "modeling", "industry 4.0", and "maintenance" frequently emerged in 2021. In addition, more comprehensive research expansion in this area happened in 2022 (keywords=20) and 2023 (keywords=8). The results show the interconnection and interoperability research with other digital technologies, such as "blockchain", "BIM", and "IoT", etc.

The links are the number of connections with another keyword while the total link strength shows 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 had higher total link strength. 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 digitalized maintenance research interest 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 as well as the development of basic equipment conditions and data models.

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

<Please insert Table 3 about here>

3.4 Document analysis

By setting the minimum number of citations of a document to 50, 34 out of 444 documents met this threshold. The top 15 most normalized citation articles were listed in Table 4, and it was found that Feng et al. (2023) study obtained the most normalized citations at 27.15 but relatively middle-level citation count at 82. This article was published in 2023, the newest among other articles. As such, 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 emphasize that the applications of DT research are more focused on the managerial processes and procedures, especially in the year of 2021.

Subsequently, the articles in Table 4 indicated that DT research has been integrated with existing technologies 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 were demonstrated by Xia et al. (2022) and Zhu et al. (2020). Besides, the articles about DT functions 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 size of the nodes stands for the citation number of each article. It was found that Tao et al. (2018) received the most citations at 489 with a lower level of normalized 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 studied 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 topics of these standalone articles still need to receive more attention than other articles.

<Please insert Figure 4 about here>

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4. Discussion

After reporting the results of this review study, this section mainly focuses on the mainstream research topics, research gaps, and future research directions in 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, thus, the findings could be useful for other researchers, policy makers, industry practitioners, and among others in this field. The construction sector is typically a project-based industry, as such, its O&M phase involves multiple stakeholders and complex project task requirements. Notably, the applications of DT in project O&M within the domain of project management also affect the reference value of this review paper.

4.1. Summary of the mainstream research topics of DT in project O&M

The list of selected keywords is presented in Table 3. There are interconnected links between keywords such as DT, deep learning, computer version, and fault diagnosis. In many keywords occurrences, DT is integrated with other digital technologies, such as blockchain technology, AI, BIM, virtual reality (VR), etc. These digital technologies could transform the construction industry, enabling changes in project O&M procedures and processes while operating real-time production activities. As a result, the mainstream research topics of DT in project O&M are summarized below.

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

Emerging digital technologies such as AI and their functions can enrich DT applications, efficiency and development. As shown in Table 3, AI, deep learning, transfer learning, and ML were all ranked at a relatively higher level of occurrence. DT enables the connection between real-time virtual and physical worlds with fault diagnosis and prediction functions to optimize 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 by using numerous 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 have integrated DT with specific AI models to monitor machine health conditions and predict their longevity through historical data dynamic comparison (Zhang et al., 2023c) as well as facilitating the reliability of managers' O&M decision-making. DT provides the simulation environment to train AI algorithms and models, which are similar to people learning knowledge in solving O&M problems (Bordegoni and Ferrise, 2023). For example, to increase DT data efficiency and accuracy, the data collection costs could be controlled to solve data latency problems (Gao et al., 2023), and enhance DT application scale in real industrial production process. Xia et al. (2023) integrated DT with transfer learning and cloud-based models for faults diagnosis of DC/DC converter to support power supply systems maintenance strategy. On the other hand, the simulation model and analysis of ML require longer training time, which limits the models' application, but DT's virtual world replicates the physical world to modify and develop AI models, thus, improving production and operation efficiency (Jain and Narayanan, 2023). Integration these digital technologies can unravel practical and research challenges as well as 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 space systems management to ensure the efficiency of a project and fulfill the demands of project customers and users (Zhao et al., 2022). Table 3 also incorporates keywords like "cloud computing", "remaining useful life" and "service-oriented architecture". AI and DT applications can sufficiently renew project O&M methods and generation. As such, facility and project managers can design equipment management and operation plans while supporting 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 occur in buildings, DT can be aligned with BIM models (Pan and Zhang, 2021), information communication technology (ICT), and mixed reality (MR) (Wu et al., 2022), 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

Emerging digital technologies have brought changes to traditional construction methods and 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 scholars have demonstrated in-depth applications for smart manufacturing, smart energy, and smart homes. Notably, smart city relies on IoT, GIS, BIM, AI, and other technologies in Industry 4.0, and 5.0 environment to reduce operational human involvement through an intelligent method to realize sustainable urban O&M. This creates a sustainable urbanization process which increases the security, cost-saving, and intrinsic connections of cities (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 to improve climate change and traffic flow issues. DT can be integrated with GIS and other geographic technologies to realize real-time traffic network monitoring and assessment. AI and IoT-enabled smart traffic systems were developed by Zhu et al. (2019) to predict the operational outcomes that may arise from specific cases so as to plan, design, operate, and maintain smart urban traffic system control. City transport infrastructure maintenance, such as bridges, roads, and railways, can be operated and maintained through DT-enabled data-driven methods (Wang et al., 2023). In addition, keywords such as "anomaly detection" (Lu et al., 2020b), "sensor", "synchronization", etc. emphasize the real-time data update and facilities fault diagnosis functions of DT, where some researchers have explored DT applications for city heritages maintenance.

Sustainability aspects include reducing product lifecycle emissions, pollution, and consumption, and the improvement of environmental, economic, and social benefits (Zhang et al., 2021). DT applications for energy performance, monitoring, and prediction maintenance have 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 studies have discussed how Industry 4.0 can influence city design and construction due to issues with resource utilization, increased energy efficiency, hazardous waste disposal, and living aspects, which could facilitate city sustainability O&M (Safiullin et al., 2019).

4.1.3. DT applications for project asset management

DT applications in project asset management have been widely 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 functions of DT in asset management. As civil engineering inevitably requires equipment/plant, how to efficiently utilize and maintain large equipment is a germane topic. DT integration with IT systems and BIM models can improve operation costs, asset health brochure generation for operators, and then construct a user-centered dashboard for various stakeholders to manage asset status from the whole project lifecycle (Keskin et al., 2022). Besides, the operational workflow design in DT environment not only relies on sensor data transmission but also assets attribution and historical data consisting of the asset administration shell for 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 can transform traditional commercial activities to achieve business value (Love and Matthews, 2019).

Although human-robot collaboration (HRC) has been discussed in recent years, there are still more studies that need to be conducted by combining the recognition and physical levels of humans and robots collaboration to realize a common goal (Sun et al., 2022). Current research has 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 using time-dependency ML. Wang et al. (2024) developed a framework to train DT data based on a neural network. They tested the developed framework in a physical system to improve the feasibility of HRC safety. Choi et al. (2022) proposed an integrated system based on MR, deep learning, DT, 3D point cloud data, and HRC for real-time human safety security, which can be applied in 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 have different implications can rather complicate the operational procedures and measurement efforts. DT as a replication of the physical world can provide a platform for safe robotic algorithm development (Baratta et al., 2023).

4.1.4. Blockchain integrated DT for project O&M

Blockchain is a distributed ledger and asymmetric encryption technology, which ensures that decentralized transaction data can be recorded and shared traceably, immutably, and transparently (Adu-Amankwa et al., 2023; Sun et al., 2023). Each project participant has a node, which is operated by computer servers to enable smart contract – a digital type of contract codification and execution for real-time payment mechanism. Blockchain technology 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 can provide building information in real-time to the blockchain, where all transaction data are traceably and immutably recorded with a timestamp, thus, facilitating project stakeholders' responsibility and understanding (Lee et al., 2021). Blockchain technology can be used to guarantee the trustworthiness of DT data so that historical data would be overwritten in the dynamic asset O&M process (Tavakoli et al., 2023). In addition, blockchain-enabled DT technology can assist cross-disciplinary stakeholders' collaboration, information sharing, tracking, resource leveling, task execution guidance in a timely manner (Jiang et al., 2023). Contract management, project quality management, and whole lifecycle management can be shaped by blockchain-enabled DT technology. In summary, blockchain technology enables collaboration within the heterogeneous social, network, and physical space resources (Li et al., 2023).

While blockchain technology and DT can be used for transactions and information-sharing, the project-based organization structure and governance approaches can influence stakeholders' relationship establishment. 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 complex logistic and inventory management process has also been demonstrated as efficient function (Pan et al., 2021; Gai et al., 2022). However, stakeholders' acceptance, operation capability, and technological understanding still hinder its real application in the construction sector.

4.1.5. DT for advanced project management

The advancement of digitalization in construction project management is still under a transition process. Digital technologies such as IoT, BIM, VR, MR, and others contribute to the transition process (Mu and Antwi-Afari, 2024; Ye et al., 2024) while DT promotes the development of advanced project management. It enables project O&M phase to automate and eliminate the procedures that involve human intervention to construct event diary logs and evaluate project performance (Pan and Zhang, 2021). Some keywords and articles primarily pertinent to the function of DT in Tables 3 and 4 include "fault diagnosis", "predictive maintenance", "condition monitoring", "synchronization", "service-oriented architecture", "fatigue", "optimization", and "anomaly detection", show 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. While project O&M is the longest stage, project complexity is relatively high and some studies have focused on the integration of modular construction, VR (Wu et al., 2022) and DT. They were used to monitor on-site assembly situations and modular installment process. DT and VR can serve as immersive training and simulation platform for robot arrangement in modular construction to mitigate onsite construction project complexity and increase safety performance (Zhu et al., 2022).

In the case of decision-making 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 and operation decision support visualized platform and framework based on DT for project and government decision-makers. Decision-making is one of the key elements of project governance, which affects project performance and satisfaction of end users and clients (Müller-Zhang et al., 2023). Risk identification and mitigation strategy can be provided by DT real-time structure health monitoring and predictive maintenance to assist service-oriented structure construction (Shi et al., 2023). Project O&M processes are generally becoming a service provision process. DT implementation can improve the efficiency and productivity of project O&M, while contributing to advanced project management knowledge fields and empirical project practice.

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

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

<Please insert Figure 5 about here>

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 and 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 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 obtain simulation results for different project tasks and events. The third stage is evaluation and decision optimization. Multiple simulation possibilities can be calculated and compared by using ML and deep learning algorithms 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 for building workflow and operators' collaboration. Many AI and DT applications in project O&M primarily proposed conceptual models without real practice and testing in industrial production scenarios (D'Urso et al., 2024). From the managerial perspective, analysis of AI systems can only execute the designed tasks, but there is lack of research on the performance of historical data accuracy and completeness. General project management regulations for AI and DT applications needs to be refined (Müller et al., 2024).

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

According to the United Nations, the urban population is expected to increase by 2.5 billion in 2050, which infers the significance of smart city and associated intelligent solutions, 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 could promote the intelligent degree of population's urban life, but traditional architectural structure can limit the implementation of emerging technologies, thus, affecting the realization and sustainable development of 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 certainly be constrained by governments of different countries as well as technical feasibility, social collaboration, and economic benefits (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 designers 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 models are essential, but cross-region city data collection and interconnection are under development due to data regulation and different laws. Since DT systems involve specific city operating data, urban safety and administration systems are distinct and may be difficult to support other cities' usage based on data demands. Therefore, there is a research gap in cross-institution and cross-region DT data framework for city information resource integration, city operation process planning and management. In addition, highly connected smart cities would increase the concern about cybersecurity. Consequently, DT applications in urban infrastructure O&M phase may face many challenges such as cybersecurity, citizens' personal data protection, regulations, policy clarification standards based on different categories of human behavior, and intelligent city models' access. It is, therefore, crucial for policymakers to consider the regulation tools and policies to promote city stakeholders' participation in smart city development and daily project 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 advanced digital technologies. As already mentioned, data latency, accuracy, and sources of historical data are the breakthrough for practical DT applications in asset management. Specifically, sensors data transmission, data integration and data storage for multiple digital technologies, large amount of data collection, and data interoperability problems would impact the application of DT in project asset management. 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. Data management processes including assets data collection, materials and systems' compatibility are the core resources for quality DT function application. Therefore, efficient integration of DT data model with sensor data and its compatibility with machinery equipment command reception system, data quality, data standards, and the restrictions on the level of authority between systems are all key factors in the project O&M stage.

Although previous studies have focused on HRC, it is the future of industrial production works. As such, current research should be conducted on how humans and robots can coordinate with existing working processes and systems. One of the challenges of HRC is the dynamic nature of human behavior and the complexity of cognition with the need for data-driven adaptation (Malik and Brem, 2021). As a result, one of the key testing solutions is using AI technology to simulate human behavior trajectory (Wang et al., 2024), but it is imperative to develop a framework for industries to describe the technologies, structures, information flow, and processes that redefined operation methods. Moreover, risk assessment standard should be suitable for HRC operational environment based on the new HRC safety standards. Wilhelm et al. (2021) found that DT can enable machines or robots' intervention for operators' safety within a VR environment, thus for detecting safety hazards and providing risk mitigation action in real-time. The whole process is a two-way interaction and information exchange between the operator and the robot. Complex industrial environments and multiple operators' collaboration in HRC environment for activity recognition and gesture evaluation are 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 technology and DT integration for project O&M

To solve the data reliability problem of DT, blockchain technology has been broadly discussed to fix data-related problems. For example, Tavakoli et al. (2023) developed a DT data resource model based on Remix Ethereum platform and Sepolia test network which enables asset model maintenance and real-time data acquisition in dynamic O&M process. Blockchain technology can reduce 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).

Due to 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 construction project supply chain management (Gai et al., 2022).

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

The level of professional competence of system operators and the complexity of contextual information also poses challenges for multi-party collaboration. The characteristics of construction project stakeholders, cross-organizational collaboration, and temporary environment sometimes limit the acceptance of digital transition. As such, complex project O&M tools like DT and AI need to develop a user-friendly dashboard in industrial practice. In addition, knowledge competence affects digital acceptance when using information and communication tools. Project decisions would be directly impacted by changes in tool use. For example, the collaboration between various enterprises, their data and information analyses, processing capabilities and compatibilities may differ. These decisions could 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 critical success factors for implementing DT in production and sustainability aspects, but the factors influencing DT adoption in organization or operational procedure haven't been explored (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. Although several advanced digital technologies have been implemented and explored in the construction industry, it particularly depends on accurate events, risk, and cost budget control in project planning phase (Regona et al., 2022). Digital technologies like AI and DT can be utilized in project O&M phase to reduce the time spent on repetitive tasks. Therefore, project managers and operators should establish a holistic digital environment for historic data activation, which is still a daunting task. Furthermore, the efficiency of project O&M cost and capital cost for implementing DT technologies would increase, but the investment performance and benefits are still unclear. These limitations hinder the adoption of DT whilst the planning, management, and procurement processes of digital systems are meant to conform with the project's financial capabilities. A research study is needed for the commercialization of DT applications with 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, as shown in Figure 6. This section is based on the former two subsections in order to obtain the future research trends.

<Please insert Figure 6 about here>

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 design and construction scenarios can be expanded to the global perspectives, and reflect multi-attribute of people, policymakers, and industries. Energy performance, intelligent construction, sustainability, etc. city development agenda should be considered 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, behavior and mitigate the detrimental effect on rational decision-making for the purposes of efficiency. The integration of various technologies would inevitably raise several issues that call for future studies, including system compatibility, the adaption of different machine interfaces, data fusion capabilities, and the best alignment of operational procedures. The investment efficiency of DT 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. Machine and deep learning algorithms could be integrated with DT for human gestures and behavior prediction within a HRC environment (Wang et al., 2024). AI and DT integration could predict human motions, behaviors, actions, which would be utilized for risk, change, cost, quality, and contract management (Müller et al., 2024).
4. **Privacy and security.** Cybersecurity and regulations should 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 could be integrated into DT and other emerging digital technologies development.
5. **O&M scenario consideration.** DT encourages the revitalization of information management, but more studies are needed to understand how data information could 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.** Future studies are recommended to enhance decision-making optimization due to incorporating users' feedback and other platforms in DT to guarantee 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 could contribute to metaverse construction.

5. Conclusions

This review paper aims to conduct the state-of-the-art research on DT applications in project O&M. It adopted a scientometric and critical review method consisting of literature search, literature selection, science mapping analysis, and qualitative discussion. In total, 444 published articles in the last 10 years (i.e., from 2014 to 2024) were retrieved from the Scopus database and included for further analyses. It was found that the number of published articles significantly increased from 2020, indicating that the attention paid to researchers and practitioners within the studied domain. In addition, 78 relevant peer-reviewed journals were selected, finding that

Automation in Construction, Journal of Manufacturing Systems, and *International Journal of Computer Integrated Manufacturing* contributed to the largest number (i.e., 52) and total percentage (i.e., 11.71%) of published articles. Moreover, the most frequently occurring keywords identified by the keyword co-occurrence analysis include “digital twin”, “internet of things”, “industry 4.0”, and “building information modeling (BIM). Some keywords were related to technology utilization scenarios like “smart city”, “smart manufacturing”, and “modular construction”. Other advanced digital technologies keywords like “AI”, “cloud computing”, “blockchain”, “sensors”, “virtual reality”, “computer vision”, etc. were found. These results indicate the relevance of integrating advanced digital technologies for solving information and data management issues in project O&M phase. In addition, the document analysis revealed that the most cited articles combined DT with other AI and data mining algorithms such as—reinforcement learning, deep learning, transfer learning, and ML—indicating a key research area for enhancing the time latency and data accuracy problems of DT, as well as providing a simulation model training platform.

From the qualitative discussion, a research framework was proposed based on the mainstream research topics, research gaps, and future research directions of DT applications in project O&M. The mainstream research topics include (1) DT-based 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 were summarized into 5 categories, namely (1) scenarios of DT and AI technology integration in project O&M, (2) challenges of DT application in smart city and sustainable development, (3) issues of information sharing and interoperability for DT application in project asset management, (4) problems of blockchain technology and DT integration for project O&M, and (5) project managers and operators’ competence challenges of DT platform alliance. Lastly, six potential future research directions were proposed including (1) smart city scenario, (2) asset data and information aggregation, (3) AI and DT integration, (4) privacy and security, (5) O&M scenario consideration, and (6) decision-making support. These findings indicate that research related to the application of DT in the construction sector is of utmost importance because of the wide range of stakeholders, huge amount of capital, lengthy O&M cycles, and the effect of hazards or risks. This review study contributes to identifying journals, keywords, documents, mainstream research topics, research gaps, and future research directions of DT applications in project O&M, thus, extending the body of knowledge of the studied topic 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 may lead to an inadequate number of included articles, thus affecting the results. Second, detailed technical analyses of specific advanced digital technologies in project O&M scenarios are lacking, providing only an overall theoretical framework and operational views for this phase. Third, the literature search was conducted in January 2024 within the Scopus database, and only included journal articles written in English, thus excluding conference papers and articles in other languages. These exclusion criteria may affect the generalization of the results.

To address the limitations, future studies should include in-depth explanation of the advanced digital technologies related to DT systems for project O&M, along with illustrative examples. Next, incorporating specific case studies would have improved the technical explanation, making them simpler to understand and implement. In addition, project managers must improve their digital expertise 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. 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

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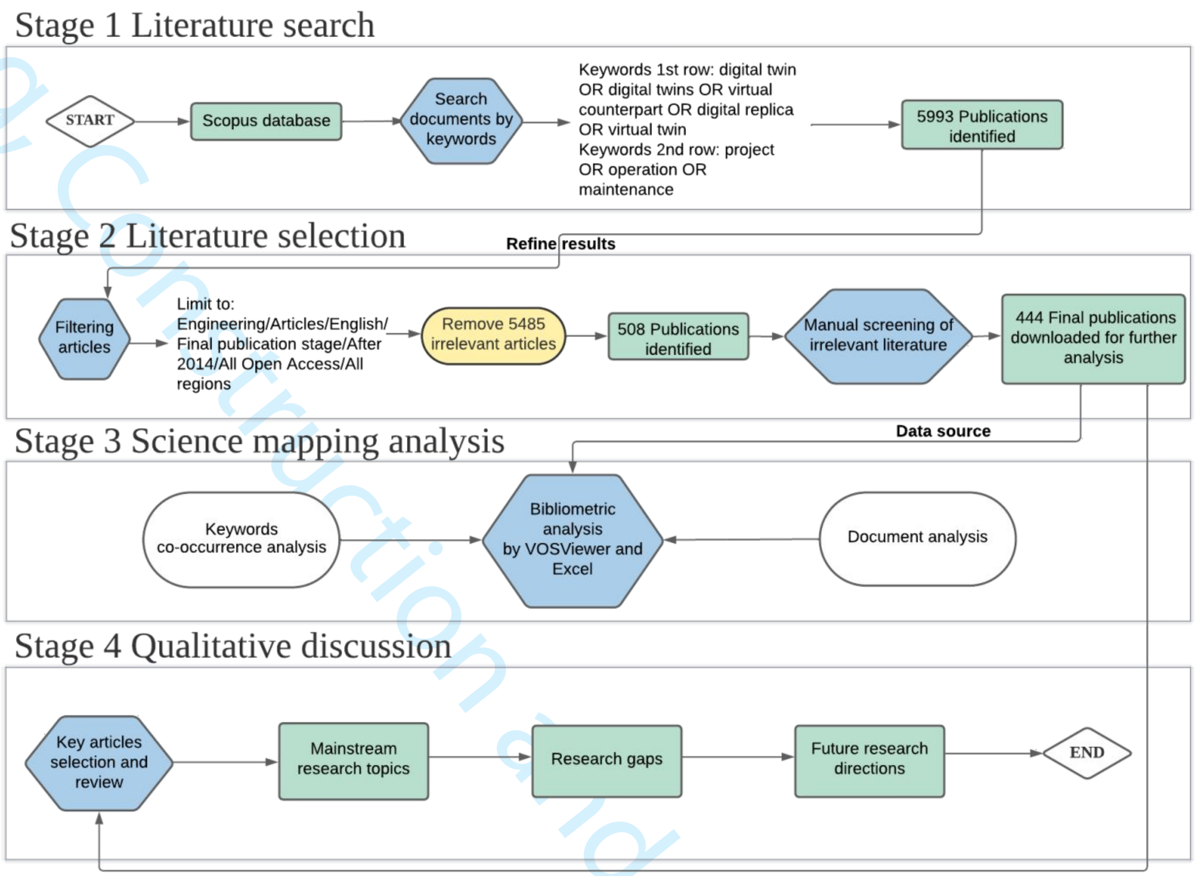

Fig. 1. An overview of the research process (**Source:** Authors' own work)

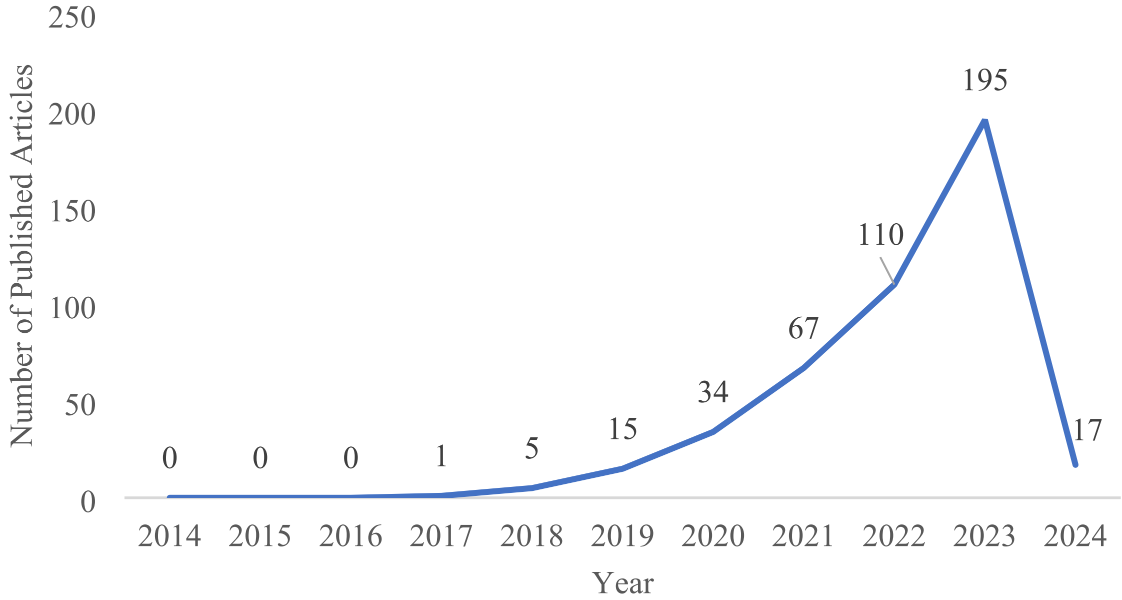

Fig. 2. Annual publication trend of articles in DT in project O&M (A total of 444 articles). **Note:** The articles were published from 2014 to 2024 (at the end of January 2024) (**Source:** Authors' own work)

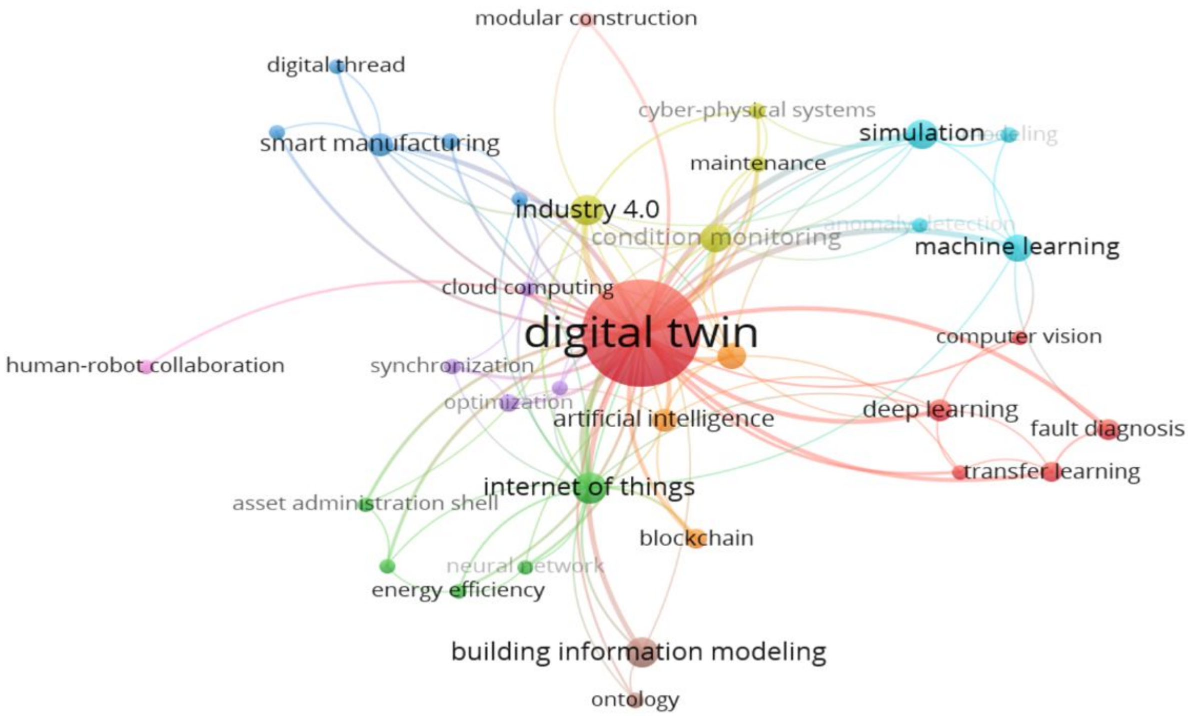

Fig. 3. Keywords co-occurrence network of DT in project O&M. **Note:** VOSviewer was used to generate and visualize the network diagram (**Source:** Authors' own work)

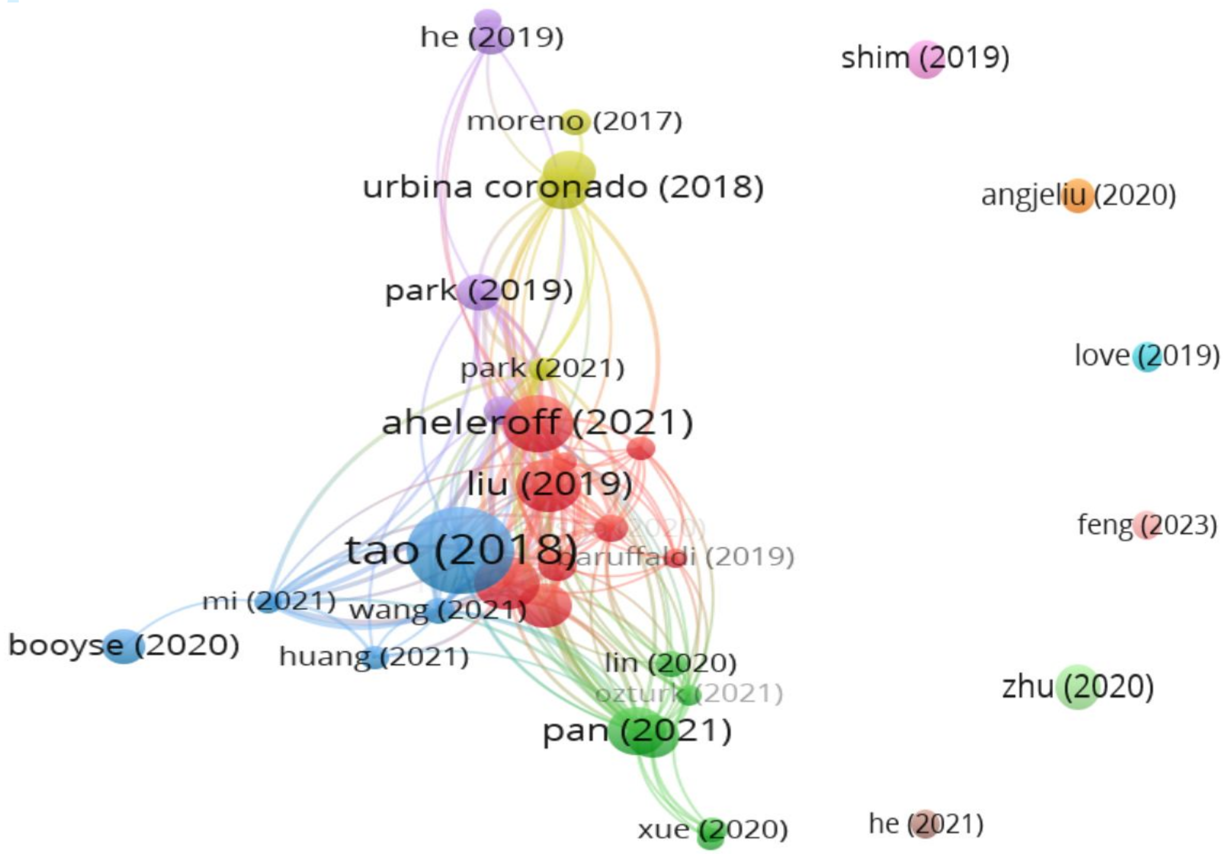

Fig. 4. Document network analysis of DT in project O&M. **Note:** VOSviewer was used to generate and visualize the network diagram (**Source:** Authors' own work)

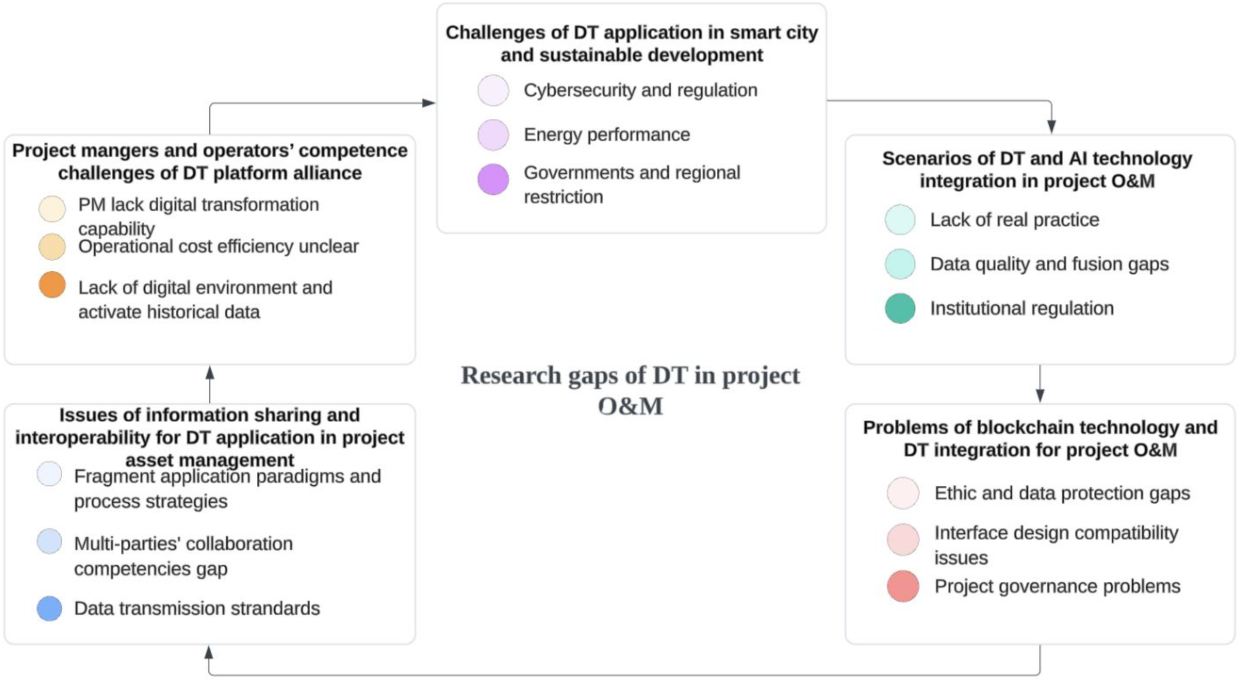

Fig. 5. Research gaps of DT applications in project O&M (**Source:** Authors' own work)

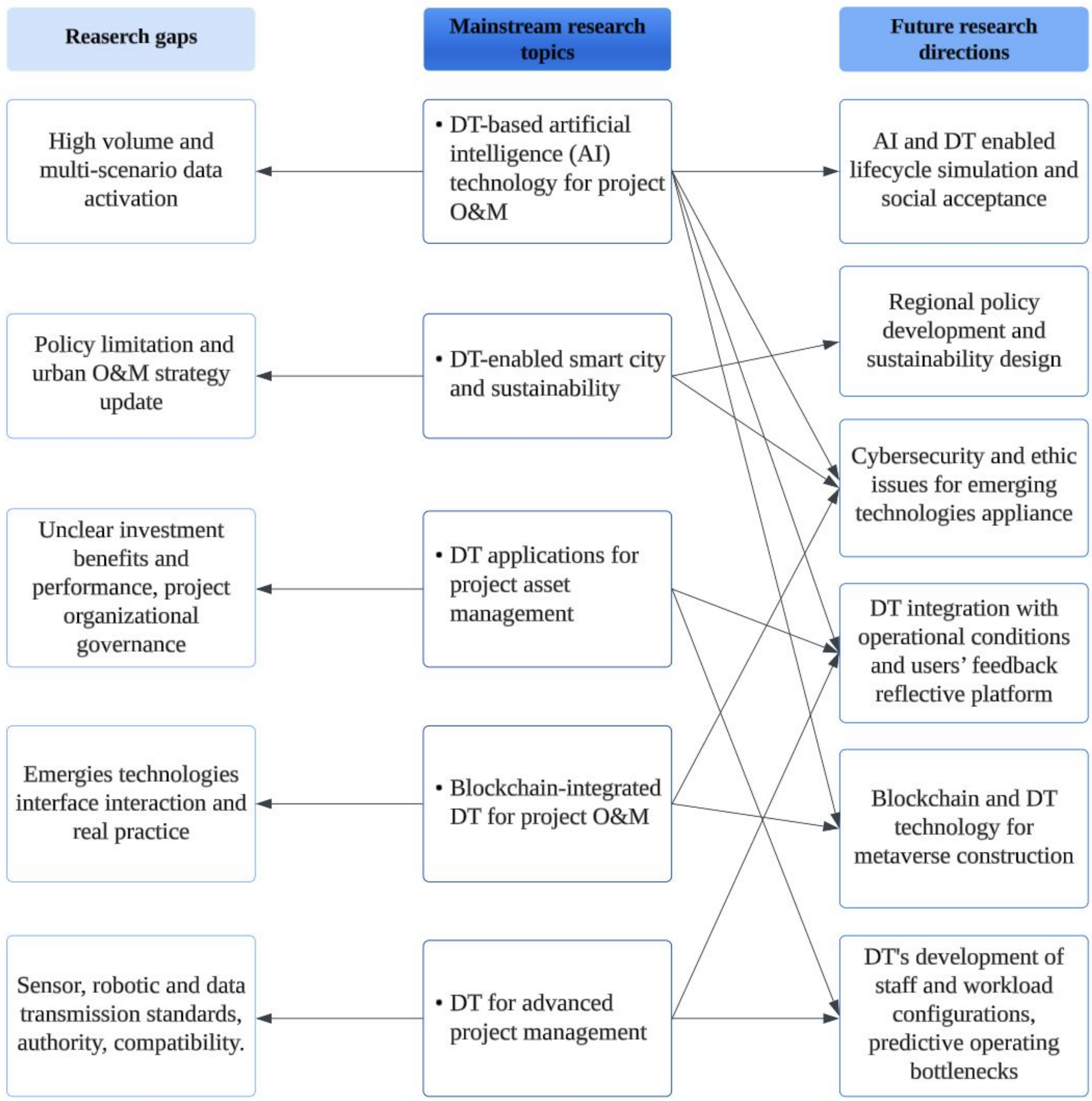

Fig. 6. Research framework showing the links between mainstream research topics, research gaps, and future research directions (**Source:** Authors' own work)

Table 1. Search strings and results

Query Strings	Results
((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
Manual screening of irrelevant literature. Literature selection and exclusion criteria were discussed in Section 2.2.	444

Note: Scopus search was done in January 2024. (**Source:** Authors' own work)

Table 2. Top 20 selected peer-reviewed journals

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 & 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**

(**Source:** Authors' own work)

Table 3. List of keywords 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

(**Source:** Authors' own work)

Table 4. Top 15 cited articles published from 2014 to January 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 individualized 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

(**Source:** Authors' own work)