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REVIEW ARTICLE

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Digital twin-enabled smart facility management: A bibliometric review

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Abstract In recent years, the architecture, engineering, construction, and facility management (FM) industries have been applying various emerging digital technologies to facilitate the design, construction, and management of infrastructure facilities. Digital twin (DT) has emerged as a solution for enabling real-time data acquisition, transfer, analysis, and utilization for improved decision-making toward smart FM. Substantial research on DT for FM has been undertaken in the past decade. This paper presents a bibliometric analysis of the literature on DT for FM. A total of 248 research articles are obtained from the Scopus and Web of Science databases. VOSviewer is then utilized to conduct bibliometric analysis and visualize keyword co-occurrence, citation, and co-authorship networks; furthermore, the research topics, authors, sources, and countries contributing to the use of DT for FM are identified. The findings show that the current research of DT in FM focuses on building information modeling-based FM, artificial intelligence (AI)-based predictive maintenance, real-time cyber–physical system data integration, and facility lifecycle asset management. Several areas, such as AI-based real-time asset prognostics and health management, virtual-based intelligent infrastructure monitoring, deep learning-aided continuous improvement of the FM systems, semantically rich data interoperability throughout the facility lifecycle, and autonomous control feedback, need to be further studied. This review contributes to the body of knowledge on digital transformation and smart FM by identifying the landscape, state-of-the-art research trends, and future needs with regard to DT in FM.

Keywords digital twin, building information modeling, facility management, semantic interoperability, artificial intelligence, intelligent monitoring, autonomous control feedback

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1 Introduction

The operation and maintenance (O&M) phase in facility lifecycle management is particularly critical (Ali et al., 2010; Coupry et al., 2021) because this phase is the longest and costliest period in the lifecycle of facilities. Despite this, it has been given relatively little attention (Lu et al., 2020b). Currently, a comprehensive asset management plan and the ability to record, analyze, and use asset-related data are lacking when it comes to O&M (Lu et al., 2020b). In this context, a smart facility management (FM) approach is demanded to sustain the serviceability and safety of facilities. To achieve smart FM, asset management must be integrated from the design and construction phase to the O&M phase and be digitalized (Al-Kasasbeh et al., 2020; 2021). To this end, researchers have targeted the application of digital technologies for FM throughout the facility lifecycle. For example, in the last two decades, building information modeling (BIM) has been widely studied within the FM domain with the aim of improving facility maintenance, energy performance management, fire emergency evacuation, indoor environment monitoring, and occupant comfort, to name a few notable applications (Khajavi et al., 2019; Liu et al., 2020). However, the need for real-time monitoring and intelligent feedback has led to the evolution of BIM toward digital twin (DT). It should be noted that DT is a prominent technology that facilitates instantaneous bidirectional integration of cyber–physical systems and supports intelligent decision-making.

According to Deng et al. (2021), DT emerged from BIM through four stages of development and integration with other technologies that involved the utilization of sensors, simulation, and artificial intelligence (AI) at various levels. Leveraging BIM, DT can integrate the information bidirectionally throughout the facility's lifecycle. DT utilizes Internet of Things (IoT) technologies, such as smart sensors, lasers, photogrammetric tools, and measuring devices, to acquire real-time status information about the given facility. Furthermore, DT, with the help of AI paradigms, such as machine learning (ML) and deep learning (DL), analyzes data in a real-time manner to monitor the condition, learn from the environment, predict system failures, and provide real-time feedback (Agnusdei et al., 2021; Deng et al., 2021; Ozturk, 2021; Almatared et al., 2022; Moiceanu and Paraschiv, 2022). DT has been shown to provide proactive maintenance and diagnostic function by continuously monitoring the status of the asset and helping to prevent failures (Florian et al., 2021; Samatas et al., 2021). Moreover, DT-based predictive maintenance has been shown to be more cost-effective than conventional methods as it only requires maintenance or replacement activity when failure or potential failure is evident (Katona and Panfilov, 2018). Thus, DT is an essential component of a smart FM program.

Given the promise of DT in FM, substantial research has been dedicated to this emerging research area, resulting in many academic publications on DT in FM. Nevertheless, few literature review studies have focused on DT applications for FM. In one of the few review studies in this area, Deng et al. (2021) performed a systematic review of 123 articles on the evolution of BIM to DT in the architecture, engineering, construction, and facility management (AEC-FM) industry; they found that BIM integration with simulation and IoT can aid in built environment monitoring, whereas BIM integration with AI facilitates real-time visualization of the built environment, real-time data-based prediction, and automatic control feedback. Almatared et al. (2022) conducted a bibliometric analysis of DT in the AEC industry and concluded that data interoperability issues still represent an obstacle to effective data exchange, asserting that the use of DT technologies during the design, construction, and O&M phases of the facility could assist with data integration. Ozturk (2021) conducted a scientometric analysis and mapping of DT in the AEC-FM industry, examining 151 papers obtained from the Scopus database to highlight the research pattern and gaps, finding that big data collected through IoT could be used for FM and that a considerable gap exists in information-based predictive management and utilization of information through virtual models.

Although these systematic and bibliometric literature reviews have examined DT applications in the AEC-FM industry from many aspects, no previous study has provided a holistic and specialized review of specific FM activities, such as facility asset management, during the O&M phase. Moreover, the current practice of DT for FM mainly focuses on the as-built BIM and AI or ML for energy and maintenance management. Thus, a clear picture of the manner in which DT can be used to serve the FM sector systematically and how the in-depth integration between DT and FM might be achieved is needed. However, what has been achieved (i.e., research trend) and what the focus of future research should be remain unclear. The landscape of DT in FM, such as major outlets, authors, institutions, topics, and so forth, also remains unclear. This review explores state-of-the-art research literature on DT in FM, contributes to the body of knowledge through its quantitative synthesis of research trends, topics, sources, authors, institutions, and co-authorship, and identifies future research directions.

2 Methods

This paper aims to provide a landscape view of the emerging DT in FM. Specifically, a bibliometric analysis of DT in FM was used to reveal the landscape. Traditional and qualitative reviews draw conclusions based on the critical analysis of a limited number of papers and expert knowledge (Liu et al., 2020). By contrast, the present review conducts a quantitative analysis of a large amount of state-of-the-art literature on DT for FM to identify the landscape and presents a holistic analysis of author keyword co-occurrence, clustering, document citations, author/co-authorship, source, and country. Furthermore, the challenges associated with the identified research topics are presented, and future research needs are identified.

As shown in Fig. 1, the bibliometric analysis consisted of three steps: 1) literature search, 2) bibliometric analysis, and 3) a comprehensive discussion of the results. First, the literature was retrieved from two sources, Web of Science (WoS) and Scopus. Two literature databases were included to ensure more comprehensive coverage of existing literature. Then, bibliometric analyses were performed to visualize the co-occurrences and citation networks as these networks can help identify the research trends, most prominent authors, sources, institutions, countries, and co-author relationships in the research area of DT applications in FM. Author keyword co-occurrence analysis was conducted to visualize the research themes and trends of the targeted research domain quantitatively because keyword co-occurrence shows the number of documents that contain the same keyword and are formed into clusters that allow for better representation and easy interpretation of the research theme results (van Eck and Waltman, 2022). This research used VOSviewer, a tool that uses publication data to create maps for visualization and interpretation for bibliometric analysis (van Eck and Waltman, 2022). Furthermore, visualization and exploration of the network maps that result from this exercise help inform research trends and future needs within the given field. The following subsections describe in detail each step conducted in this process.

2.1 Literature search

As noted above, the literature for the bibliometric analysis was retrieved from the Scopus and WoS databases.

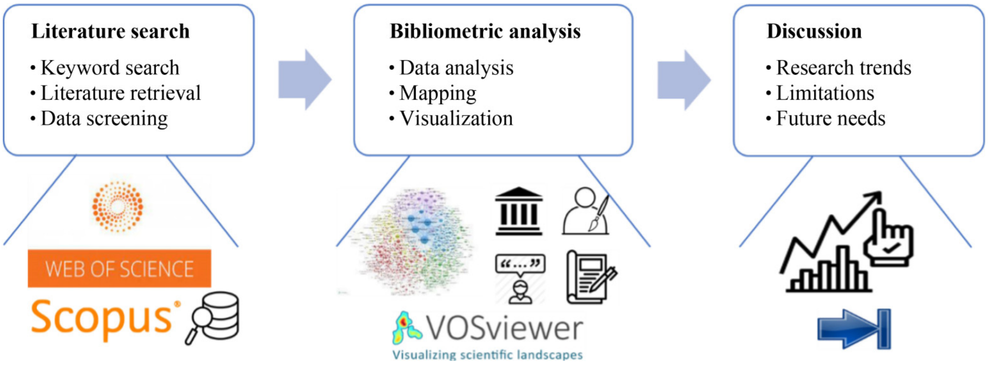


Fig. 1 Research methodology.

Scopus was chosen because it is one of the most well-established scientific abstracts and indexing databases. Compared with other similar databases, it has a more extensive literature collection (Burnham, 2006; Parlina et al., 2020; Agnusdei et al., 2021; Opoku et al., 2021). Most previous review studies in this area have used only one database as a literature source (Mongeon and Paul-Hus, 2016; Ozturk, 2021; Pranckutė, 2021; Moiceanu and Paraschiv, 2022). In this review, WoS was selected as a second source because of its extensive coverage of engineering and the natural sciences. Collecting articles from multiple databases ensures more compelling and holistic data results. However, existing bibliometric analysis tools lack the feature of being able to merge the duplicate documents that may be encountered as a result of using multiple data sources (Ozturk, 2021), and duplicates were removed manually in this study. All the documents were then compiled in a single repository for further processing/analysis.

A comprehensive search was performed in Scopus and WoS using the fields of title, abstract, and keywords. The keywords in previous review studies were used for the literature retrieval (Wong et al., 2018; Liu et al., 2020; Opoku et al., 2021). Specifically, in the first field of the search string, the keywords “Digital Twin” OR “Digital Twins” OR “Digital-twin” OR “Digital Twinning” OR “Virtual Twin” OR “Digital Replica” OR “Virtual Replica” OR “Virtual Counterpart” OR “Virtual Representation” were used. In the second part of the search string, the keywords “Facility Management” OR “Facilities Management” OR “Asset Management” OR “Facility Lifecycle Management” OR “Infrastructure Management” OR “Building Facility” OR “Operation and Maintenance” OR “O&M” OR “Smart Building” OR “Preventive Maintenance” OR “Renovation” were included. Preventive maintenance is included in this study instead of maintenance to narrow down the search toward the main purpose of DT for maintenance. DT is ideally used to prevent failures through preventive maintenance. Furthermore, after reviewing the academic publications in the field of DT-enabled FM, preventive maintenance had been mentioned as an author keyword more remarkably. Additionally, a general review of academic publications shows that DT will replace BIM in the renovation of existing facilities (Daniotti et al., 2022). The renovation in the literature search was to evaluate the extent of DT application for facility renovation practices because maintenance was more specifically considered preventive maintenance. “Virtual Counterpart” OR “Virtual Representation” is mainly interchangeably used for DT. These two keywords are also included in the literature retrieval in similar studies regarding DT (Opoku et al., 2021). As such, the selected keywords and their combination helped obtain more relevant publications (Kaewunruen and Xu, 2018; Felsberger et al., 2019; Angjeliu et al., 2020; Chen et al., 2021; Neto et al., 2021).

The period for the bibliometric literature search was set as from January 2012 to March 2022, and the language was limited to English only. In Scopus, the document types, such as conference papers and articles under the research areas of engineering, computer sciences, environment sciences, decision science, and energy, were used; in WoS, the document types include proceedings, papers, and articles under the research areas of engineering, computer sciences, construction building technology, automation control systems, science–technology, environmental science, and energy. The search resulted in 315 papers from Scopus and 110 papers from WoS, and these papers were further screened using a title and abstract review. Duplicates were removed, and 248 documents were eventually identified and manually combined. Figure 2 summarizes the process flow chart for the literature retrieval.

2.2 Overview of retrieved literature

Figure 3 shows the article distribution over time. As shown in the figure, the number of publications from 2017 to March 2022 considerably increased compared to the period between 2012 and 2017, with nearly all the papers on the topic of DT in FM being published during this period. Figure 4 shows that the concentration of DT

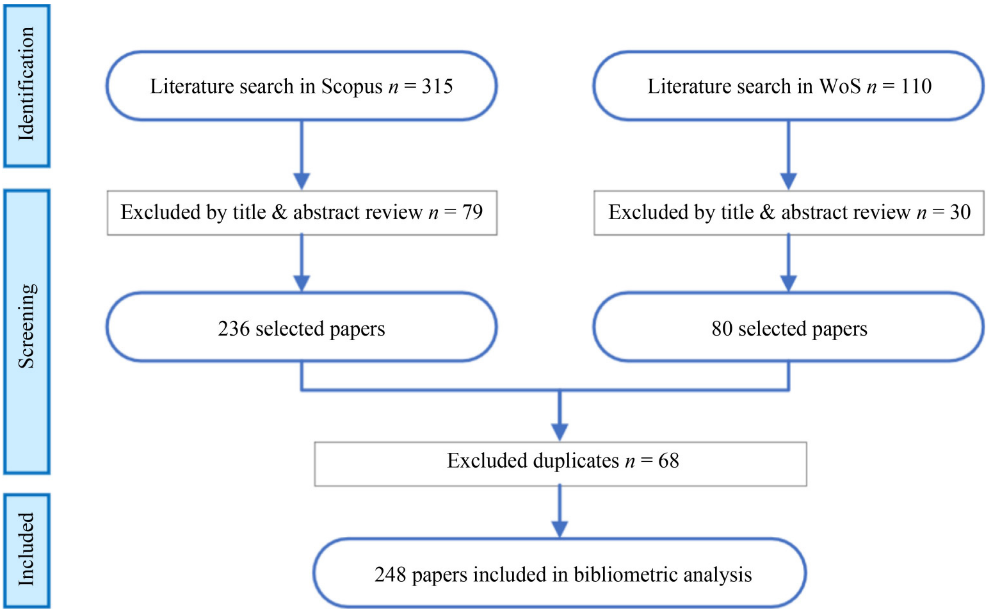


Fig. 2 Literature retrieval process.

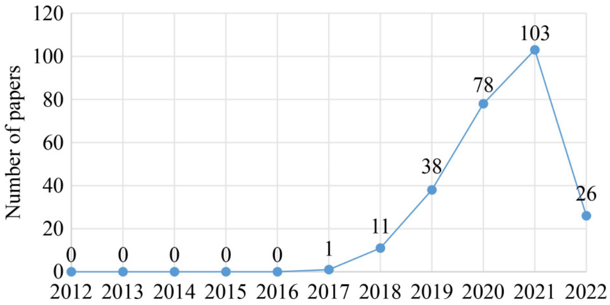
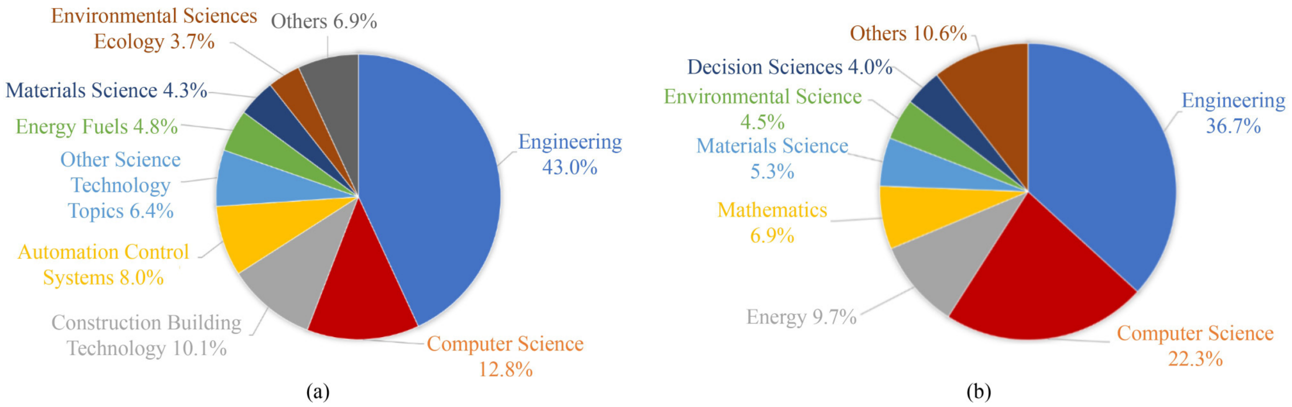


Fig. 3 Yearly number of documents published on the topic of DT in FM (January 2012–March 2022).

research within the FM field has been highly focused on the engineering and computer science domain, implying that digital transformation and intelligent automation approaches in FM are mainly computer-aided and engineering-centric.

The distribution of academic documents in various fields indicates that the highest concentration of publications is in engineering, followed by computer science, energy, construction building technology, and automation control systems. The reason is that the digital transformation of the AEC industry and the need for smart FM require computer-aided technologies that facilitate cyber–physical system integration. Automation and instantaneous control feedback require the use of AI, such as ML and DL, which are computer-centric. In addition, Construction 4.0 is the transformation of construction practices to embrace digital technologies, such as BIM, augmented reality (AR)/virtual reality (VR), AI, and IoT, for smart construction practices. Construction 4.0 uses smart construction building technologies, robotics for construction, digitalization, and automation to integrate the planning and design phase with O&M while also facilitating real-time monitoring, predictive maintenance, and automatic control feedback throughout the facility lifecycle. Meanwhile, sustainable and smart facility operation



(a) (b)

Fig. 4 Distribution of publications on the topic of DT in FM in various research fields: (a) WoS and (b) Scopus.

demands energy performance management and indoor environment monitoring and comfort. This demand may be the reason for energy being the focus of many studies on DT in FM.

Figure 5 presents the classification of scientific documents published on DT in FM from January 2012 to March 2022 by publication type. As shown in the figure, 55% of the publications identified are conference papers, whereas 45% are journal articles.

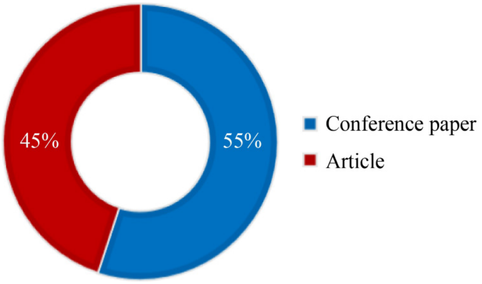


Fig. 5 Scientific publications on the topic of DT in FM by document type.

3 Bibliometric results

The bibliometric analysis mainly focuses on studying documents, authors, keywords, and sources through network mapping and clustering (Waltman et al., 2010). This section presents the results of bibliometric analysis and the corresponding network visualization maps.

3.1 Co-occurrence of author keywords

All the documents identified from Scopus and WoS were fed into VOSviewer to identify co-occurrences of author keywords. The threshold for keyword occurrences was set at 3. A thesaurus file was developed and used for data cleaning. A thesaurus file identifies the redundant keywords and combines them with one label to enhance network visualization (van Eck and Waltman, 2022). A total of 36 of the 701 keywords met the criteria. These keywords that met this threshold were mapped in the keyword network and were visualized, as shown in Fig. 6.

Each node in Fig. 6 represents one keyword, whereas

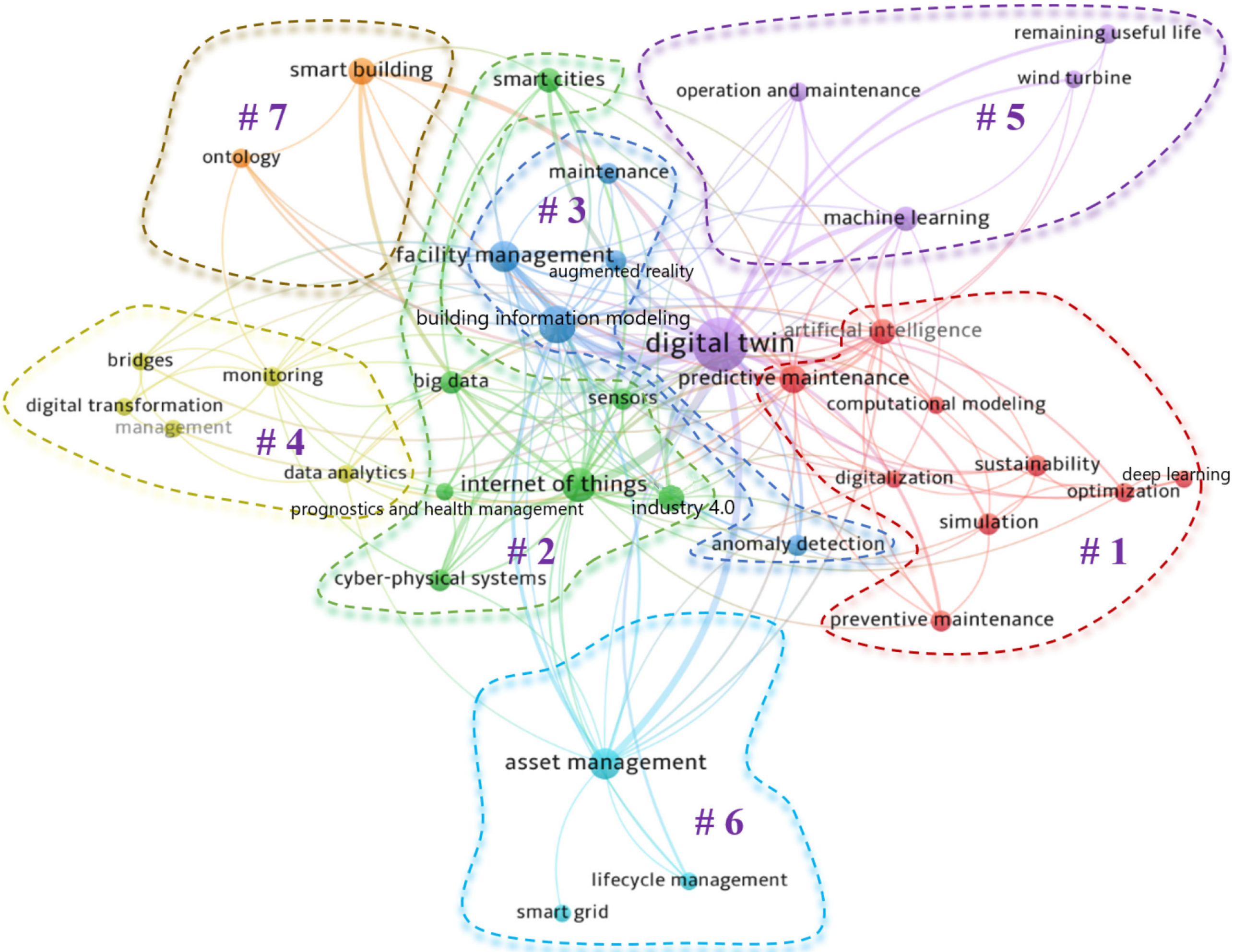


Fig. 6 Co-occurrence network of author keywords related to DT in FM.

the color-coded node's size represents the keyword's occurrence. The relatedness of a given keyword to other keywords is indicated by the attributes of links, i.e., the number of links and total link strength. The strength of the link indicates the number of documents in which two keywords appear together. The distance between keywords indicates the degree of relatedness between them: Close proximity between two keywords implies a strong relationship between them. The number of links to a given keyword shows its relativeness to the research clusters or topics; the higher the number of links is, the stronger the relativeness of the keyword is considered to be. The number of links and their correlation explicitly indicate the trend and are representative of the DT research in the FM industry.

The co-occurrence analysis also identified seven clusters through this process, and their constituent keywords are listed in Table 1. The clusters were named as listed on the basis of the most prominent topic to which the keywords in the cluster are related, keeping with the principles of information theory. The color coding in Fig. 6 and noted in parentheses for each cluster in Table 1 indicates the cluster to which each keyword belongs. Information regarding the number of occurrences, links, total link strength, the average number of citations, and average publication year is also provided in Table 1. As shown in Table 1, the keywords were clustered into seven categories using the clustering techniques in VOSviewer, with the resulting network consisting of 36 keywords, 171 links, and a total link strength of 402. As shown in the table, "lifecycle management" received the highest average number of citations (32.00), followed by "anomaly detection" (10.80), "maintenance" (9.40), "asset management" (9.21), "Industry 4.0" (8.27), "Internet of Things" (8.21), and "digitalization" (8.00). The co-occurrence analysis of author keywords identified "bridges", "computational modeling", "operation and maintenance", "management", and "optimization" as keywords with very recent occurrences with regard to the application of DT in FM. These keywords, along with "digital twin", have mainly been in use in the scientific literature within this area since late 2020. Furthermore, all of these keywords, in the context of DT applications in FM, are relatively new, with an average publication year of late 2019. The average publication analysis indicates that the application of DT technology for FM is still new, and, with a focus on digital transformation and technology advancement, it can be expected to flourish in the coming year.

The findings with regard to the average number of citations indicate that DT in FM is still relatively new. They also show that lifecycle management is an important topic in FM, with the highest average number of citations (as noted above), whereas smart asset management, maintenance, IoT, and digital transformation are also important topics in this area. The keywords related to enabling technologies of DT and its application for FM with the lower average number of citations were found to be "prognostics and health management" (3.67), "machine learning" (1.89), "artificial intelligence" (1.60), "sustainability" (1.40), "simulation" (1.00), and "deep learning" (0.67). Again, further research is needed with regard to AI/VR-based sustainable FM, computerized maintenance management systems, DT-based intelligent infrastructure monitoring, and semantic interoperability for smart asset management. The following subsections describe the identified clusters in further detail.

3.1.1 AI-based predictive maintenance (red)

The most prominent keywords in this cluster were "predictive maintenance", with 13 occurrences and a total link strength of 40; "artificial intelligence", with 10 occurrences and a total link strength of 31; and "simulation", with 6 occurrences and a total link strength of 9. The degree of relatedness of these keywords and their link strength indicate that AI must be utilized to achieve predictive maintenance goals and sustain the operation of the facility.

This cluster presents the research area of predictive maintenance and AI-based algorithms of ML and DL intended to facilitate smart maintenance. AI, such as ML and DL, shows tremendous potential in real-time data analysis, minimizing maintenance costs and optimizing the facility's operational performance (Cardoso and Ferreira, 2021). Predictive maintenance, for instance, is a diagnostic strategy that continuously evaluates the condition of the asset through various sensors. It also uses AI-based algorithms to provide automatic feedback so that action can be taken when needed to avoid failure and unnecessary incurrence of costs (Florian et al., 2021; Samatas et al., 2021). AI-based predictive maintenance and anomaly detection have thus been the focus of many recent research studies within the FM sector aimed at facilitating real-time data acquisition, analysis, and utilization for effective decision-making (Lu et al., 2020b; Xie et al., 2020; Samatas et al., 2021). The main challenge in achieving effective AI-based predictive maintenance is that most existing facilities do not have digital models that would facilitate the application of AI computational models and learn from the process to enhance improved and proactive decision-making. Thus, "computational modeling", with 3 occurrences and a total link strength of 5, "deep learning" (3, 4), and "digitalization" (3, 9) are the least studied keywords in this cluster and the most recently studied topics, with an average publication year of late 2021, 2021, and late 2019, respectively. Thus, the digitalization of built assets, AI technology, the application of simulation for FM, and the use of computational modeling through computerized maintenance management systems to simulate, visualize, analyze, and manage assets throughout the lifecycle

Table 1 Most frequently occurring keywords in research on DT in FM

Clusters and their keywords	Occurrences	Links	Total link strength	Avg. number of citations	Avg. publication year
Cluster 1: AI-based predictive maintenance (red)					
1. Artificial intelligence	10	16	31	1.60	2020.80
2. Computational modeling	3	4	5	0.00	2021.67
3. Deep learning	3	3	4	0.67	2021.00
4. Digitalization	3	9	9	8.00	2019.67
5. Optimization	4	6	7	1.25	2021.25
6. Predictive maintenance	13	17	40	4.00	2020.77
7. Preventive maintenance	5	6	9	7.00	2020.40
8. Simulation	6	7	9	1.00	2020.50
9. Sustainability	5	7	9	1.40	2020.80
Cluster 2: Real-time cyber–physical integration (green)					
1. Big data	7	11	18	3.14	2020.57
2. Cyber–physical systems	6	10	16	6.17	2020.50
3. Industry 4.0	11	14	24	8.27	2020.27
4. Internet of Things	29	20	68	8.21	2020.10
5. Prognostics and health management	3	8	10	3.67	2020.33
6. Sensors	5	12	16	2.80	2020.80
7. Smart cities	9	9	19	5.56	2020.44
Cluster 3: Digital FM (blue)					
1. Anomaly detection	5	6	9	10.80	2020.20
2. Augmented reality	5	8	13	6.40	2020.20
3. Building information modeling	40	20	81	7.43	2020.40
4. Facility management	20	20	56	6.85	2020.50
5. Maintenance	5	5	6	9.40	2020.60
Cluster 4: As-built/As-is modeling (yellow)					
1. Bridges	3	6	8	0.00	2021.67
2. Data analytics	3	7	8	5.00	2020.33
3. Digital transformation	3	4	4	1.00	2021.00
4. Management	3	5	6	0.00	2021.33
5. Monitoring	4	13	13	3.50	2020.25
Cluster 5: Intelligent prognostics and health management (purple)					
1. Digital twin	139	34	192	5.09	2020.52
2. Machine learning	9	12	22	1.89	2020.89
3. Operation and maintenance	4	5	8	0.75	2021.25
4. Remaining useful life	4	3	6	5.50	2020.50
5. Wind turbine	3	4	6	1.33	2021.00
Cluster 6: Asset lifecycle management (light blue)					
1. Asset management	19	14	36	9.21	2020.26
2. Lifecycle management	3	4	6	32.00	2019.67
3. Smart grid	3	1	1	0.00	2020.00
Cluster 7: Semantic interoperability (brown)					
1. Ontology	4	5	8	1.00	2020.00
2. Smart building	12	7	21	3.58	2020.33

toward smart FM must be further explored through research and case studies.

3.1.2 Real-time cyber–physical integration (green)

Data acquisition and integration have been the focus of many studies. As evidence of this trend, the most influential keywords in this cluster were identified as "Internet of Things", with 29 occurrences and a total link strength of 68; "Industry 4.0" (11, 24), "smart cities" (9, 19), and "big data" (7, 18). "Sensors", with 5 occurrences and a total link strength of 16, and "prognostics and health management" (3, 10) are the least studied topics in this cluster and are attracting increasing attention in recent research, with an average publication year of late 2020 and early 2020, respectively. These findings indicate that having real-time data sensing of facility operation is vital. However, to achieve real-time asset management, integrating the big data gathered from the physical asset with its virtual counterpart is also vital. In this regard, DT is a technology that connects the physical entity to its virtual model in real-time; it can precisely predict failures and integrate high-quality data into virtual and physical products (Ozturk, 2021).

This cluster emphasizes the importance of real-time data acquisition through IoT technologies and the integration of digital models with their physical counterparts. Real-time cyber–physical integration facilitates data-driven interconnectivity and automation in FM practices.

3.1.3 Digital FM (blue)

The most important keywords in this cluster were found to be "building information modeling", with 40 occurrences and a total link strength of 81, and "facility management" (20, 56). The results indicate that BIM is highly related and required for smart FM. BIM is an essential component of the DT paradigm and is used as a source of information on existing facilities. As such, the use of BIM as a means of facilitating smart FM has been the focus of extensive research (Liu et al., 2020). Meanwhile, the results show that "augmented reality", with 5 occurrences and a total link strength of 13, "anomaly detection" (5, 9), and "maintenance" (5, 6) have been the least studied topics in this cluster. AR has been shown to be useful in particular applications, such as in fire emergency evacuation for showing the optimal route and guiding the occupant to safety (Zhu and Li, 2021), and for tracking construction progress by superimposing a virtual model on the physical space (Schiavi et al., 2022). However, the holistic application of AR for FM warrants further study because a solution for accurately superimposing the geometry of the VR model on its physical counterpart has yet to be proposed. Similarly, while DT technology and as-is BIM models for anomaly detection in manufacturing, transmission systems, smart grid, wind turbines, engines, and other machines have been widely studied, and the associated benefits have been explored, a comprehensive FM approach for intelligent anomaly detection in smart maintenance has yet to be established (Zeng et al., 2020; Xie et al., 2020; Wang et al., 2021).

3.1.4 As-built/As-is modeling (yellow)

In this cluster, the most influential keyword was found to be "monitoring", with 4 occurrences and a total link strength of 13, followed by "bridges" (3, 8), and "data analytics" (3, 8). These results demonstrate that smart infrastructure monitoring and management can be achieved by digitalizing assets and utilizing automatic data analytics algorithms. Civil infrastructure refers to the fundamental facilities that ensure the sustainable operation of the economy and society. In many developed countries, civil infrastructure is deteriorating and requires smart monitoring and maintenance (Shim et al., 2019). In this regard, DT technology can be used to, for example, create virtual models of bridges for real-time condition monitoring, performance evaluation, automatic feedback, and decision-making (Shim et al., 2019; Ye et al., 2019; 2020). The results for this cluster indicate that "digital transformation", with 3 occurrences and a total link strength of 4, and "management" (3, 6) are the least studied topics in this cluster and the focus of recent studies, with an average publication year of early 2021.

This cluster emphasizes the need for digitalization and the creation of digital models for infrastructural assets. Creating an as-built or as-is model is an important step in the real-time monitoring process because it allows for creating and managing a digital representation of the infrastructure that reflects its actual physical and functional characteristics. Smart infrastructure monitoring and management can be achieved by digitalizing assets and utilizing automatic data analytics algorithms.

3.1.5 Intelligent prognostics and health management (purple)

The most prominent keywords in this cluster were found to be "digital twin", with 139 occurrences and a total link strength of 192, and "machine learning" (9, 22). The results indicate that health monitoring and estimating the remaining useful life of a facility during the O&M phase require the application of DT technology. DT technology can be used to update databases in real-time and facilitate effective O&M of facilities. AI technologies, such as ML, have been widely studied and have been shown to be effective tools for organizing and analyzing the big data collected in real-time using IoT technologies. ML, in particular, facilitates automation in decision-making and has been applied for various purposes in the fields of smart manufacturing, prognostics, health management, energy, transportation, and smart cities (Rathore et al., 2021). In this cluster, "wind turbine", with 3 occurrences and a total link strength of 6, was found to be the least studied keyword. The result indicates that DT application for smart infrastructural asset management is the least studied topic. In addition, to achieve smart FM, the facility's remaining useful life during the O&M phase must be understood through real-time intelligent monitoring.

This cluster focuses on remaining useful life estimation and facility health monitoring. Remaining useful life estimation and structural health monitoring are essential parts of FM; however, civil facilities lack intelligent prognostic systems for accurate health monitoring. DT has the potential for remaining useful life prediction, whereas real-time monitoring technologies are used to collect complex data, and holistic ML algorithms are developed to facilitate the integration of historical data; their fusion with the heterogeneous data from several parts of the structure provides an accurate indication regarding the health of the facility. Estimation of the remaining useful life of an asset assists facility managers with budget allocation and scheduling for renovation or disposal. While AI-based predictive maintenance utilizes real-time data to identify potential issues before they occur and schedule maintenance activities accordingly, remaining useful life estimation is used to predict the remaining lifespan of an asset.

3.1.6 Asset lifecycle management (light blue)

The most influential keyword in this cluster was found to be "asset management". This cluster presents the importance of FM throughout the lifecycle. Facility asset management has been the focus of a considerable volume of research, and its advantages have been widely explored. However, the concept of lifecycle management, which considers the management of a facility from planning to construction to O&M, is a relatively new concept that emerged in the 21st century (Ozturk, 2021).

3.1.7 Semantic interoperability (brown)

"Smart building" was found to be the most influential keyword in this cluster, with 12 occurrences and a total link strength of 21. "Ontology" was found to be the least prominent keyword, with 4 occurrences and a total link strength of 8. Smart buildings utilize intelligent technology and BIM to achieve efficient, comfortable, and sustainable FM throughout the lifecycle (Baracho et al., 2019). This cluster indicates that meaningful interoperability is essential for achieving smart FM.

3.2 Citation analysis

3.2.1 Documents

Citation analysis was applied to gain insights into the most influential publications on the topic of DT in FM. In VOSviewer, the minimum number of citations of a document was set at 30, resulting in the identification of the 10 most cited documents in this area. A closer look at the 10 most cited documents reveals that most documents are focused on theory. This finding suggests that the application of DT in FM is still early in its maturation and requires more case studies and practical applications. A detailed look at the 10 most cited publications on DT application in FM (listed in Table 2) also underscores the

Table 2 Most cited documents on DT application in FM

No.	First author	Title	Source	Year	Number of citations
1	Jain P	*A digital twin approach for fault diagnosis in distributed photovoltaic systems*	*IEEE Transactions on Power Electronics*	2020	74
2	Wong J K W	*Digitization in facilities management: A literature review and future research directions*	*Automation in Construction*	2018	73
3	Macchi M	*Exploring the role of digital twin for asset lifecycle management*	*IFAC-PapersOnLine*	2018	70
4	Sivalingam K	*A review and methodology development for remaining useful life prediction of offshore fixed and floating wind turbine power converter with digital twin technology perspective*	*Proceedings of the 2nd International Conference on Green Energy and Applications*	2018	48
5	Lu Q	*Developing a digital twin at building and city levels: Case study of West Cambridge campus*	*Journal of Management in Engineering*	2020	43
6	Shim C S	*Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model*	*Structure and Infrastructure Engineering*	2019	40
7	Love P E D	*The "how" of benefits management for digital technology: From engineering to asset management*	*Automation in Construction*	2019	39
8	Kaewunruen S	*Digital twin for sustainability evaluation of railway station buildings*	*Frontiers in Built Environment*	2018	39
9	Lu Q	*Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance*	*Automation in Construction*	2020	38
10	Wagg D J	*Digital Twins: State-of-the-art and future directions for modeling and simulation in engineering dynamics applications*	*ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*	2020	30

importance of DT for real-time asset monitoring and predictive maintenance and sheds light on the advantages, DT limitations, and future research needs of DT in asset management.

For instance, Jain et al. (2020) developed a highly sensitive DT approach for fault diagnosis in distributed photovoltaics with remarkable potential for application in smart buildings, conducting simulation and experimental studies to validate their DT model. Similarly, Lu et al. (2020b) presented and successfully tested a DT-enabled anomaly detection system for asset monitoring and its data integration based on extended industry foundation classes (IFC) for daily O&M management. Using centrifugal pumps in a heating ventilation air conditioning (HVAC) system as a case study, they modified the IFC schema to include the data received from the pump (e.g., ifcpump) and used ifcObject matching to link the BIM model of the pump with the sensor ID in the sensor system. They also used vibration sensors to monitor the operation behavior and vibration frequency of the pump and used AI and a Bayesian online change point detection algorithm to identify and filter anomalies from normal operation through cross-checking.

Wagg et al. (2020) presented a state-of-the-art method of DT application in engineering dynamics, describing a wind turbine case as an example of asset management. Their work also presented a case study of a three-story structure to illustrate the modeling challenges associated with applying DT in the construction phase. A mathematical framework was developed for DT application in engineering dynamics. Shim et al. (2019) proposed a DT-based bridge maintenance system for effective decision-making; they used a 3D model connected to a digital inspection system that uses image processing in combination with data obtained across the lifecycle of the project from the initial phases of design and construction to O&M. Similarly, Sivalingam et al. (2018) proposed a physics-based DT framework that helps predict the useful life of offshore wind turbines and facilitates predictive maintenance. Moreover, Kaewunruen and Xu (2018) explored a sustainability evaluation model using DT. They used a Revit-based simulation of construction activities for a building at a railway station, considering a 6D BIM application encompassing time, cost, and carbon emission estimation. Lu et al. (2020a) presented a comprehensive framework for DT development at the building and city levels; the system architecture was used to create a DT of the West Cambridge site at University of Cambridge in the UK, a resource that facilitates the integration of data from various sources, supports effective data acquisition and analysis, facilitates decision-making during the O&M phase, and strengthens the relationship between humans and buildings/cities.

Wong et al. (2018) conducted a holistic, systematic review of the importance of digitization in FM. Their review encompassed various DTs for FM and shed light on future research needs (e.g., data interoperability, and BIM/geographic information system (GIS) asset database integration). Similarly, Macchi et al. (2018) presented a state-of-the-art exploratory study emphasizing the importance of DT for decision-making in asset lifecycle management. Meanwhile, Love and Matthews (2019) explored the potential benefits of DT adaptation for asset management. Their study relied on empirical findings from nine projects evaluating the benefits of digitalization for asset management. They concluded that digital transformation and system information modeling could generate considerable business value and productivity.

3.2.2 Sources

Sources of academic publications are great indicators of the value and significance of the research literature. To present a broader list of sources for academic publications through VOSviewer, the following 10 sources were identified: 1) *Automation in Construction*, 2) *Journal of Management in Engineering*, 3) *Applied Sciences*, 4) *Sensors*, 5) *Procedia Manufacturing*, 6) *Sustainability*, 7) *Proceedings of the Annual Offshore Technology Conference*, 8) *Journal of Building Engineering*, 9) *IEEE Access*, and 10) *Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference*. To identify the most relevant sources in the field of DT application in FM, in VOSviewer, the minimum number of documents was set at 5, and the minimum number of citations of a source was set at 10. Table 3 lists the most relevant sources, whereas Fig. 7 maps the links between these sources. The results show that *Automation in Construction* was found to be the most relevant source, with 9 documents published on DT in FM, receiving 192 citations in total, with an average of 21.33 citations per document and an average publication year of 2020.11. The second most influential source, *Applied Sciences*, had 7 publications, receiving a total of 49 citations representing an average of 7.00 citations per document and an average publication year of 2020.43. The third most influential source, *Sustainability*, was found to have published 6 papers on the topic of DT in FM, receiving 21 citations in total for an average of 3.50 citations per document and an average publication year of 2020.83. The fourth most relevant

Table 3 Most cited sources of academic publications on DT application in FM

No.	Source	Documents	Citations	Avg. publication year	Avg. citations
1	*Automation in Construction*	9	192	2020.11	21.33
2	*Applied Sciences*	7	49	2020.43	7.00
3	*Sustainability*	6	21	2020.83	3.50
4	*IEEE Access*	6	12	2021.17	2.00
5	*Sensors*	5	11	2021.00	2.20

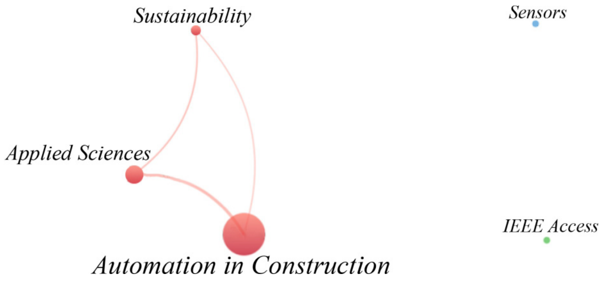


Fig. 7 Network mapping of the most cited sources of academic publications on DT in FM.

source was *IEEE Access*, which published 6 documents, garnering a total of 12 citations, representing an average of 2.00 citations per document and an average publication year of 2021.17. The fifth most influential source was *Sensors*, which published 5 documents, receiving 11 citations in total, representing an average of 2.20 citations and an average publication year of 2021.00. *Automation in Construction*, *Sensors*, and *IEEE Access* were found to be the sources with documents that have been published most recently (late 2020 and 2021), although the documents in *Applied Sciences* and *Sustainability* were also published quite recently (in mid to late 2020). The average publication year of the documents published in the abovementioned sources indicates that the topic of DT in FM is relatively new and has been the subject of increasing attention among scholars in recent years.

3.2.3 Authors

Through VOSviewer, a comprehensive list of 13 authors in the research field of DT in FM was extracted, including 1) Parlikad A K, 2) Xie X, 3) Schooling J M, 4) Lu Q, 5) Heaton J, 6) Woodall P, 7) Kaewunruen S, 8) Gardner P, 9) Barthorpe R J, 10) Wagg D J, 11) Worden K, 12) Ham Y, and 13) Kim J. To identify the most influential authors in the field of DT in FM, the minimum number of documents of an author was set to 4 in VOSviewer, and the minimum number of citations of an author was set at 25, yielding the five most prominent authors for the topic of DT in FM. The most relevant authors publishing on the topic of DT in FM are listed in Table 4, and their network visualization map is shown in Fig. 8. The results illustrate that Parlikad A K, affiliated with the Institute for Manufacturing, University of Cambridge, UK, is the most prominent author in the area of DT application in FM, with 10 publications that have received a total of 135 citations, representing an average of 13.50 citations per publication and an average publication year of 2020.00. The second most influential author was found to be Xie X from the Institute for Manufacturing, University of Cambridge, UK, with 8 publications that have received 114 citations in total, representing an average of 14.25 citations per publication and an average publication year of 2020.13. The third most influential author was Lu Q, from the Bartlett School of Construction and Project Management, University College London, UK, with 6 publications receiving a total of 99 citations, representing an average of 16.50 citations per publication and an average publication year of 2020.17. The fourth most influential author was Heaton J, affiliated with the Institute for Manufacturing, University of Cambridge, UK, has 4 publications receiving a total of 74 citations, representing an average of 18.50 citations per publication and an average publication year of 2019.75. The fifth most influential author on the topic of DT in FM was found to be Schooling J M from the Centre for Smart Infrastructure and Construction, University of Cambridge, UK, who authored 4 documents on the topic of DT in FM, receiving a total of 54 citations, representing an average of 13.50 citations per publication and an average publication year of 2020.00. The results of the analysis show that the University of Cambridge is at the frontier of research on DT in FM.

Table 4 Most relevant authors for the topic of DT in FM

No.	Author	Documents	Citations	Avg. publication year	Avg. number of citations
1	Parlikad A K	10	135	2020.00	13.50
2	Xie X	8	114	2020.13	14.25
3	Lu Q	6	99	2020.17	16.50
4	Heaton J	4	74	2019.75	18.50
5	Schooling J M	4	54	2020.00	13.50

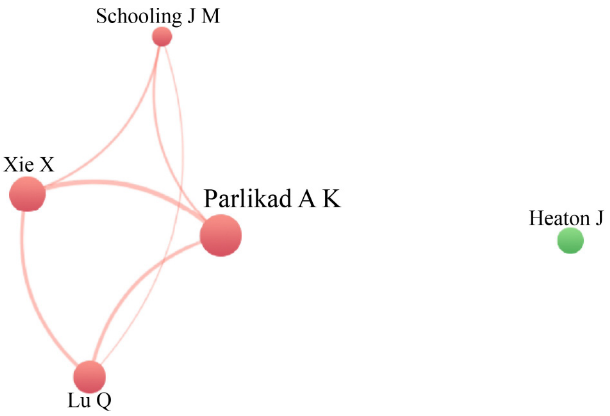


Fig. 8 Network visualization of most cited authors in the research area of DT in FM.

3.2.4 Countries

In VOSviewer, the minimum number of documents of a country was set at 5, and the minimum number of citations of a country was set at 30 to obtain the 10 most influential countries with regard to research on DT in FM.

The results indicate that the UK is the highest contributing country with respect to research on DT in FM, with 38 publications garnering 297 citations in total, an average of 7.82 citations per publication, and an average publication year of 2020.39. The second most influential country was found to be the US, with 27 publications receiving 193 citations in total, with an average of 7.15 citations per publication and an average publication year of 2020.30. The US was followed closely by Italy, with 32 publications garnering a total of 192 citations, representing an average of 6.00 citations per publication. Italy was followed by Australia, China, Germany, South Korea, Norway, Spain, and Finland.

Even though China has been productive in terms of the number of publications (51 documents), the UK has been the most influential country, with its documents being highly cited by other academic publications. Furthermore, although Australia published comparatively fewer documents (9), these received 132 citations, representing an average of 14.67 citations per publication, illustrating the significance and strong impact of these documents. All the documents were found to have a recent average publication year (ranging from late 2019 to late 2020), indicating that the topic of DT in FM has been gaining momentum in recent years. Table 5 presents the list of the highest contributing countries, whereas Fig. 9 is the network visualization map of the most influential countries in the research area of DT in FM.

Table 5 Countries with the most highly cited publications in the research area of DT in FM

No.	Country	Documents	Citations	Avg. publication year	Avg. number of citations
1	UK	38	297	2020.39	7.82
2	US	27	193	2020.30	7.15
3	Italy	32	192	2020.53	6.00
4	Australia	9	132	2020.22	14.67
5	China	51	98	2020.88	1.92
6	Germany	13	92	2019.62	7.08
7	South Korea	7	79	2019.86	11.29
8	Norway	8	43	2020.00	5.38
9	Spain	5	38	2020.20	7.60
10	Finland	8	33	2020.13	4.13

3.3 Co-authorship analysis

3.3.1 Authors

To identify instances of research collaboration in the area of DT in FM, the minimum number of documents by a given author was set at 4 in VOSviewer. The minimum number of citations garnered by a given author was set at 25, yielding a list of five authors representing the highest co-authorship strength with respect to the topic of DT in FM. Table 6 presents the co-authorship analysis of authors, including their total link strength, the number of documents they have published, and the number of citations received. Figure 10 provides the network visualization map of the collaboration between authors in the research area of DT in FM.

As also shown in the results of the citation analysis of authors, the co-authorship analysis of authors indicated that the most prominent authors coauthoring documents in the area of DT applications for FM are Parlikad A K, with a total link strength of 22, Xie X (20), Lu Q (17), Schooling J M (12), and Heaton J (7). All the mentioned authors are from either University of Cambridge or University College London in the UK.

3.3.2 Countries

Scientific collaboration helps maximize the impact of research by exchanging ideas and skills. Thus, understanding the international scientific collaboration trends and identifying prominent scientists and countries in the field of DT in FM are essential. To understand the connection and degree of cooperation between countries with respect to DT in FM, the five most cooperative and connected countries were determined accordingly. The minimum number of documents of a country was set at 5 in VOSviewer, and the minimum number of citations of a

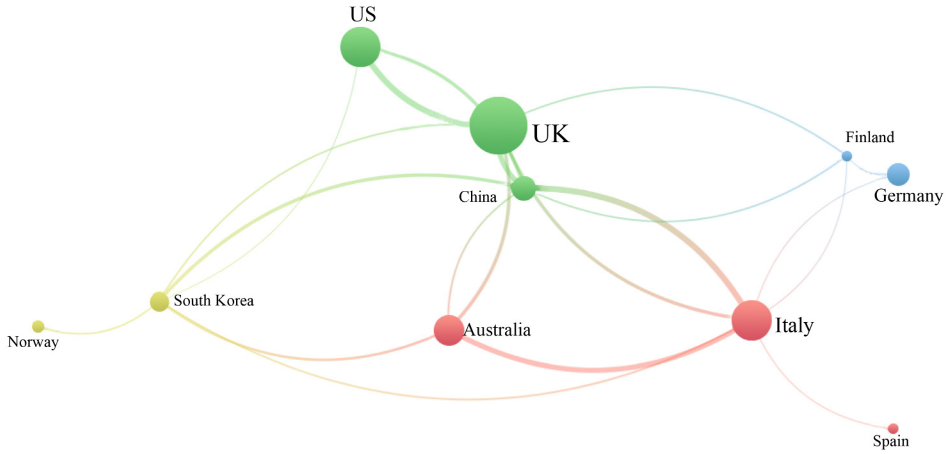


Fig. 9 Network mapping of countries with the most cited academic publications on DT in FM.

Table 6 Authors exhibiting the highest degree of collaboration in the area of DT in FM

No.	Author	Total link strength	Documents	Citations
1	Parlikad A K	22	10	135
2	Xie X	20	8	114
3	Lu Q	17	6	99
4	Schooling J M	12	4	54
5	Heaton J	7	4	74

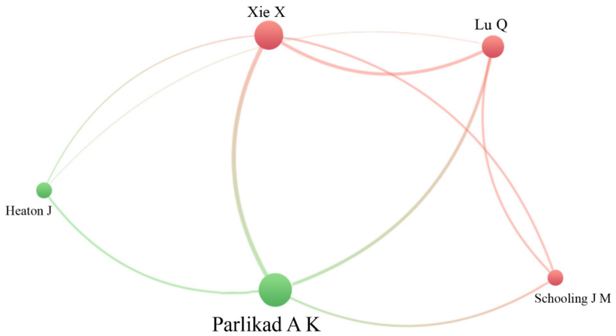


Fig. 10 Network visualization map of co-authorship analysis of authors publishing on the topic of DT in FM.

country was set at 95. Table 7 summarizes the most collaborative countries in terms of co-publishing scientific documents on the topic of DT in FM internationally, whereas Fig. 11 shows the link and network mapping of international co-authorship of scientific documents in the research area of DT in FM by country. The analysis indicated that China is the most prominent country, with its researchers having co-published 51 documents internationally and having a total link strength of 7. China was followed by the UK, with its researchers having coauthored 38 publications with researchers from other countries, representing a total link strength of 6. Italy was found to be the third most influential country, with authors from Italy having co-published 32 documents internationally, representing a total link strength of 3. Researchers from the US, meanwhile, coauthored 27 publications with researchers from other countries, representing a total link strength of 4. Finally, Australia was identified as the fifth prominent country with Australian authors having contributed to 9 internationally coauthored documents.

4 Discussion and future needs

The author keyword clustering analysis identified seven main research areas of DT applications in FM. These areas include 1) AI-based predictive maintenance, 2) real-time cyber–physical integration, 3) digital FM, 4) as-built/as-is modeling, 5) intelligent prognostics and health management, 6) asset lifecycle management, and 7) semantic interoperability. In general, monitoring and collecting real-time data from assets through IoT technologies, analyzing the data for informed decision-making and control feedback, and integrating the physical asset with the corresponding BIM model for information visualization are vital. BIM, IoT, predictive maintenance, and asset management were found to be the most studied topics in the research area of DT in FM. Automation and smart FM require the digitalization of built assets, utilization of computational modeling for data analytics, continuous improvement of FM systems, AR/VR-based visualization for facility maintenance, and AI-based real-time asset prognostics and health management. All these were the research focus in 2021 and are warranted for further research. Specifically, future research areas include 1) the potential of DT for prognostics and health management of facilities; 2) the creation of fully automated and semantically rich DT of the existing infrastructural assets; 3) interoperability of semantically rich data between BIM and FM; 4) intelligent anomaly detection for smart maintenance; 5) DT applications in facility lifecycle management, and 6) the use of big data collected using IoT technology in combination with ML algorithms for data analysis and utilization. This section provides an in-depth discussion of each research area in an attempt to reveal the research challenges, limitations, and future needs.

Table 7 Most highly collaborative countries with respect to research on DT in FM

No.	Country	Total link strength	Documents	Citations
1	China	7	51	98
2	UK	6	38	297
3	Italy	3	32	192
4	US	4	27	193
5	Australia	0	9	132

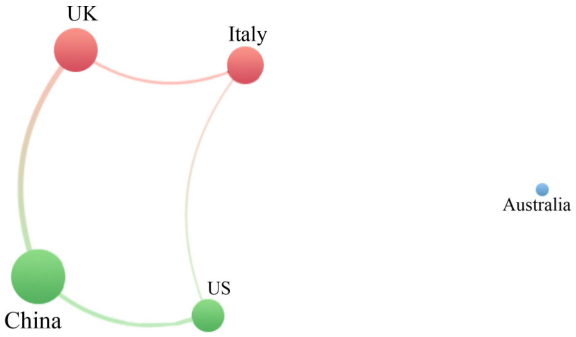


Fig. 11 Network mapping of co-authorship of scientific documents on the topic of DT in FM by country.

4.1 AI-based predictive maintenance

Predictive maintenance is a diagnostic strategy that continuously evaluates the asset's condition on the basis of sensor-collected data. It demands AI-based algorithms to provide automatic feedback so that action can be taken when needed to avoid failure and unnecessary incurrence of costs (Florian et al., 2021; Samatas et al., 2021). AI, such as ML and DL, show tremendous potential in real-time data analysis, minimizing maintenance costs and optimizing the facility's operational performance (Cardoso and Ferreira, 2021). Simulation has also been proven to be able to optimize real-time data utilization for predicting performance, optimizing maintenance, and easily accommodating changes (Wagg et al., 2020). Thus, since 2020, predictive maintenance has garnered more attention than preventive maintenance to achieve sustainable and smart maintenance management. Preventive maintenance is conducted on the basis of a prescheduled plan to avoid failure. However, conducting a given maintenance activity at the scheduled time may not be necessary, meaning that preventive maintenance is not a cost-efficient strategy (Samatas et al., 2021). By contrast, predictive maintenance is a fully autonomous, smart, and sustainable strategy that monitors the condition of the asset and predicts future failure and remaining useful life accordingly. Predictive maintenance is more cost-effective than preventive maintenance because it only prescribes a maintenance or replacement activity when imminent failure is evident (Katona and Panfilov, 2018).

AI-based failure detection using sensor-gathered data is a straightforward application for a specific type of failure; however, predicting failures that indirectly impact the data from various sensors is a challenge (Klein and Bergmann, 2019). AI applications for FM are data imbalanced because failures are rare during the facility's life cycle in comparison with normal operations. It would lead to discrepancies in the performance of the algorithms that tend to classify the most occurring instances to train the model for prediction and eventually reduce the precision of the failure prediction (Klein and Bergmann, 2019; Cardoso and Ferreira, 2021; Samatas et al., 2021). As such, future research should focus on AI for the appropriate interrelation and interpretation of data from various sensor streams. Given such data imbalance, how to fuse human inputs into the sensor-collected data for reliable decision-making (i.e., human in the loop) remains unclear and a challenge. In addition, algorithms that transfer learning from a failure model, instead of predefined attributes, must be implemented. Learning from the process concept, which continuously monitors the data and learns from the operation process, must be considered.

4.2 Real-time cyber–physical integration

DT technology collects real-time data (e.g., environmental data, human feedback, and certain product data), leveraging all kinds of IoT sensors (e.g., closed circuit television (CCTV), cameras, radio frequency identification (RFID), and so forth). These data could be transferred using a wireless sensor network. The utilization of IoT in DT-based FM and its associated benefits have been widely studied. In this regard, a digital transformation and technological revolution through real-time data integration, automation, cyber–physical systems, and interconnectivity are required to achieve smart FM. The emergence of new technologies facilitating rapid interconnectivity and process automation led to the fourth industrial revolution known as Industry 4.0 (Moiceanu and Paraschiv, 2022). In this respect, IoT technology is a critical factor in the Industry 4.0 revolution because it links the physical and digital domains in real time to allow for comprehensive collaboration. As such, IoT in the context of Industry 4.0 was widely studied in 2020, with its associated benefits well documented.

IoT and cyber–physical systems also play a crucial role in achieving smart cities because they can assist with collecting and exchanging the required data for improved operation and management of civil infrastructure assets. In this regard, the main challenges in real-time data acquisition in FM are the ability of sensors to read complex civil facility-related data and the interoperability of a large set of data that needs to be exchanged between various systems and analyzed for improved decision-making. Furthermore, IoT sensors are supposed to capture high volume and high velocity of data in real time. Data acquisition through sensor networks on the extensive facility level remains challenging due to the sensor network connectivity problems between heterogeneous devices and the interoperable exchange with the IoT gateway (Rathore et al., 2021). The real-time data acquisition of multiple facilities through IoT tools and system integration with stakeholders is still not reliable (Villa et al., 2021). To utilize this big data for prediction and decision-making, the storage, management, processing, analysis, visualization, and exchange of data, which remain a big challenge and focus of current research, are vital (Rathore et al., 2021). Future research must focus on large-scale heterogeneous sensor network interconnectivity and utilization of AI for managing, processing, and exchanging big data.

4.3 Digital FM

BIM enables effective and efficient data integration throughout the lifecycle of the facility (Xie et al., 2020). BIM models contain semantically rich information on the facility components that can be used to understand the condition of the facility and have been deployed in such applications as fire emergency evacuation, energy management, and facility operation (Pishdad-Bozorgi, 2017). During the O&M phase, BIM-enabled FM can help with information retrieval, locating assets, energy optimization, and smart maintenance scheduling. Although BIM has been extensively utilized as the source of virtual information for smart FM, data requirements from BIM to FM activities and interoperability are still big challenges (Liu et al., 2020). The interoperability of semantically rich data is another notable challenge. Fortunately, IFC, as an open international data format, has the potential to resolve the interoperability issue and help information exchange without loss of semantics (Di Ciaccio et al., 2021). Lu et al. (2020b) presented a DT-enabled anomaly detection system for asset management and its data integration based on extended IFC for daily O&M management. They used centrifugal pumps in the HVAC system as a case study and modified the IFC schema to include the data that are received from the pump (e.g., ifcpump); they also used ifcObject to link the BIM model of the pump with the sensor ID in the sensor system. However, IFC still has many limitations for facility indoor localization, such as geometric errors and challenges with querying dynamic information with IFC data (Liu et al., 2021). The quantitative results also indicate that AI, such as ML and DL, are core technologies with the potential to facilitate smart FM due to their capacity to organize big data effectively for use in informed decision-making. Therefore, future research on BIM for FM can focus on managing and exchanging real-time data using extended IFC schema for facility indoor localization.

4.4 As-built/As-is modeling

The challenges with smart infrastructure monitoring and management are the difficulty and complexity associated with monitoring all facility assets in real-time (given that civil facilities are typically large and complex and entail a high degree of variability). However, most infrastructure lacks digital and semantically rich models; digital transformation and the creation of as-built models are necessary for infrastructure monitoring and management (Lu and Brilakis, 2019). Remote sensing and point clouds are promising solutions for achieving this (Lu and Brilakis, 2019; Liu et al., 2020). Various smart technologies have been explored for routine monitoring of infrastructure facilities, e.g., multitemporal interferometric synthetic aperture radar (MT-InSAR) for deformation measurement, localized structural health monitoring sensors, and nondestructive testing (NDT) (Macchiarulo et al., 2022; Tosti et al., 2021). Still, the magnitude and remoteness of the infrastructure assets make real-time monitoring (i.e., capturing performance data) economically unviable. In addition, integrating information from satellite and in-situ NDT is still a challenge; furthermore, the permanent scatterer for MT-InSAR has limitations with target accuracy and reliability for large/fast deformations (Macchiarulo et al., 2022; Tosti et al., 2021). Therefore, future research must focus on algorithms of robust satellite data that can capture accurate structural health-related information. In addition, energy-efficient IoT systems are demanded to transmit fast and reliable data for smart infrastructure monitoring and management (Macchiarulo et al., 2022; Khujamuratov et al., 2022). Further study is needed on the creation of fully automated and semantically rich DT of existing infrastructural assets.

4.5 Intelligent prognostics and health management

Remaining useful life estimation and structural health monitoring are essential parts of FM; however, civil facilities lack intelligent prognostic systems for accurate health monitoring. The major challenge with civil facilities' intelligent prognostics is the limitation of current IoT in accurately predicting the remaining useful life due to various construction materials, complex functionality of structural members, and complex failure mechanisms. To resolve this issue, future research should focus on DT application for intelligent prognostics and facility maintenance, where real-time monitoring technologies are used to collect complex data, and holistic ML algorithms are developed to facilitate the integration of historical data and their fusion with the heterogeneous data from several parts of the structure and provide an accurate indication regarding the health of the facility. Although DT has been successfully applied in industrial, aerospace, and energy fields to predict the remaining useful life of assets, the study of its application during the O&M phase of the facility for prognostics and predicting the remaining useful life of facilities is still at its infancy, and further research is required (Toth et al., 2019; Kang et al., 2021; Congress and Puppala, 2021; Liu et al., 2022; Nguyen et al., 2022).

4.6 Asset lifecycle management

The challenges with an asset management approach that spans the entire lifecycle are integrating data from the design and construction phase with the O&M phase and decision-making in consideration of lifecycle performance. The need for an automated and unified data integration system is evident. In this regard, DT, though an emerging technology, has already been well-established as a solution for lifecycle asset management. Nevertheless, the full-scale application of DT in FM for asset lifecycle management, especially during the O&M phase, warrants further study. Simulation-based lifecycle performance prediction is also demanded to provide evidence in lifecycle decision-making. As such, DT applications in facility lifecycle management, along with the use of IoT technology for big data acquisition, data integration from construction to the O&M phase, and the use of ML algorithms for data analysis and utilization, could be further explored in future research (Ozturk, 2021).

4.7 Semantic interoperability

Smart buildings can be achieved through smart monitoring and data integration of cyber–physical systems during the O&M phase. In this context, information integration and data-rich models have been the focus of research on DT in FM. Digital models provide a rich source of data on the facility's components; however, in current practice, historical O&M data must be manually updated in the digital model. DT has the potential to address this limitation and facilitate data integration and exchange in real time for smart asset management. Furthermore, knowledge modeling can aid in smart monitoring and decision-making through its capability of representing domain knowledge. However, a practical solution for the exchange, data integration, and interoperability of semantically rich data from the as-built environment collected through various means (e.g., photogrammetry tools, sensors, and video cameras) and inspection reports to the virtual model for informed decision-making in FM has yet to be realized. Knowledge modeling must be further explored in future research (Liu et al., 2020; Coupry et al., 2021). In addition, several most important factors for smart FM during the O&M stage are anomaly detection, interoperability of semantically rich data, and prediction of the remaining useful life of assets through computerized technologies, computation modeling, and knowledge modeling (Lu et al., 2020b). Thus, future research in this area should focus on applying computerized maintenance management systems for DT in FM.

In summary, as revealed by the in-depth discussion, the challenges associated with DT implementation are the seamless integration of the physical entities with the BIM model, interoperability, big data management, and complexities with information utilization and integration throughout the facility lifecycle. Furthermore, the existing literature is mainly based on theoretical frameworks, and implementation-based research that provides practical insight is considerably lacking. AI-based predictive maintenance and prognostics play a crucial role in efficient and cost-effective facility operation; however, it still has a huge gap in the FM industry. In this regard, and to tackle this issue, BIM, IoT, predictive maintenance, AI, and asset management were found to be the most studied topics in the research area of DT in FM. In addition, results from this research indicate that digitalization of the built assets, DL technology, and use of computational modeling through computerized maintenance management systems to simulate, visualize, analyze, and manage assets throughout their lifecycle for smart FM were the focuses of some research in 2021. In addition, the application of DT for prognostics and health management of facilities; creating fully automated and semantically rich DT of the existing infrastructural assets; interoperability of semantically rich data between BIM and FM; intelligent anomaly detection for smart maintenance; and DT applications in facility lifecycle management, along with the use of big data collected through IoT technologies in combination with ML algorithms for data analysis and utilization, should be areas of focus in future research. Moreover, the essential components of automation and smart FM, DL-based continuous improvement of the FM systems, AR/VR-based visualization for facility maintenance, and AI-based real-time asset prognostics and health management must be explored in the future.

5 Conclusions

This research provides a comprehensive landscape view of DT-enabled FM and addresses the state-of-the-art research patterns, challenges, and needs of DT research in the FM field by performing a bibliometric analysis of retrieved literature. The literature in the bibliometric analysis was retrieved from two major scientific databases (Scopus and WoS). VOSviewer was used to analyze the resulting literature quantitatively, which spanned the period from January 2012 to March 2022. Network visualization mapping and analysis were used to study the co-occurrence of author keywords, citation networks, and co-authorship to identify the research trends and the most prominent authors, sources, institutions, countries, and coauthor relationships.

The major findings show that 1) AI-based predictive maintenance, 2) real-time cyber–physical integration, 3) digital FM, 4) as-built/as-is modeling, 5) intelligent prognostics and health management, 6) asset lifecycle management, and 7) semantic interoperability have been the principal focus areas of recent research on DT in FM. However, AR-BIM integration for FM, AI-based prognostics of the facility during the O&M phase, and DT-based intelligent infrastructure monitoring must be further studied to leverage DT in smart FM further. This study characterizes the current state-of-the-art and future needs with respect to research on the application of DT in FM, and in this regard, represents a notable contribution to the body of knowledge on digital transformation and smart approaches in FM. The presented review provides a quantitative overview of the landscape and cannot provide a comprehensive, critical review of the identified articles. The future directions may not be comprehensive. A critical analysis of each identified article could be conducted in the future to offer a systematic in-depth insight into this emerging research area.

Competing Interests The authors declare that they have no competing interests.

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