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Integration of Building Information Modeling and Digital Twins in the Operation and Maintenance of a building lifecycle: A bibliometric analysis review

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A R T I C L E I N F O

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A B S T R A C T

The operation and maintenance (O&M) phase of the building life cycle is the costliest and longest, yet it has received limited research attention regarding its integration with Building Information Modeling (BIM) and Digital Twins (DT). This study employs bibliometric analysis and systematic literature review (SLR) to explore this underdeveloped research area. Using data from 385 academic publications in the Scopus database, VOSviewer was applied to create, visualize, and analyze maps of countries, journals, documents, and keywords based on citation, co-citation, collaboration, and co-occurrence data. Clustering analysis identified five emerging themes: "Tech-Driven Sustainability," "Digital Built Environment," "Data-Driven Infrastructure," "Digital Transformation in Heritage Maintenance," and "Digital Integration for Architectural Efficiency," which were further analyzed through SLR. The findings reveal that nearly 45 % of these publications were produced in the last 16 months, reflecting the field's accelerating growth and collaborative nature, with an average of four authors per publication. However, the dominance of conference papers over peer-reviewed journal articles and the limited contributions from regions such as the Middle East, Africa, and South America indicate gaps in research coverage and geographic representation. By bridging the gap between theoretical research and practical application, this study identifies key challenges, barriers, and future research directions, contributing to the field by offering a roadmap for advancing and optimizing O&M processes through BIM and DT integration.

1. Introduction

The way the Architecture, Engineering and Construction (AEC) sector manages building assets throughout their lifecycle has changed significantly in recent years due to technological advancements in software, frameworks, and application tools. This is especially true when it comes to automating Facilities Management (FM) tasks to increase productivity during the operation and maintenance (O&M) phase [1]. According to Refs. [2] and [3], the O&M phase of facility lifecycle management is especially important since it lasts the longest and is the most expensive phase of a building's facility lifespan—15–25 times longer than the design and construction stages [4]. Despite this, it has not received much attention [5]. For O&M, there is currently a lack of a thorough asset

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management plan as well as the capacity to collect, process, and utilize asset-related data [5]. Furthermore, this phase involves numerous stakeholders, making it much harder to accurately locate the facility space, manage O&M records, and coordinate diverse data formats from different FM systems [6]. As a result, the traditional method of FM that depends on manual labor may have several drawbacks, such as a high rate of errors, lost time and money, and data loss [7]. To guarantee appropriate building performance for the owners and occupants, FM managers face significant hurdles due to these issues. To maintain the serviceability and safety of facilities in this situation, a smart facility management (FM) approach is required. Asset management needs to be digitalized and integrated from the design and construction stages to the O&M stage to achieve smart FM [8,9].

To do this, scientists have focused on using digital technology for FM across the whole facility lifecycle [1]. As it is thought to be able to produce major benefits in the O&M phase of building projects, the concept of Building Information Modelling (BIM) was brought to the forefront to address the issues with the traditional approach [10-12]. Furthermore, BIM has been extensively researched in the FM field over the past 20 years with the goal of enhancing, among other noteworthy applications, indoor environment monitoring, fire emergency evacuation, facility maintenance, and occupant comfort [13,14]. A recent study by Ref. [15] demonstrated that an integrated BIM method can minimize the time and cost of updating the databases of FM systems in the O&M phase compared to the standard manual technique, to name a few benefits of integrating BIM in the O&M phase of building projects [16]. also advanced the idea of a common data environment (CDE), in which asset information is cooperatively managed using a digital paradigm to enhance interoperability [17]. similarly showed how BIM may improve data integration and the effectiveness of decision-making among various stakeholders. Although BIM-based smart building asset management assisted managers in creating and maintaining a suitable living space for users [18], BIM has evolved toward digital twins due of the necessity for real-time monitoring and intelligent feedback [1].

Cross-referencing various data sources for building facilities information is necessary for anomaly identification of asset monitoring for O&M management [5]. Digital Twins (DTs) represent a comprehensive approach to optimizing anomaly detection, requiring a major improvement in data interoperability and reusability [5,19]. According to Ref. [5], the idea of DTs developed as a comprehensive method for managing, planning, forecasting, and highlighting building/infrastructure or municipal assets. Furthermore, it

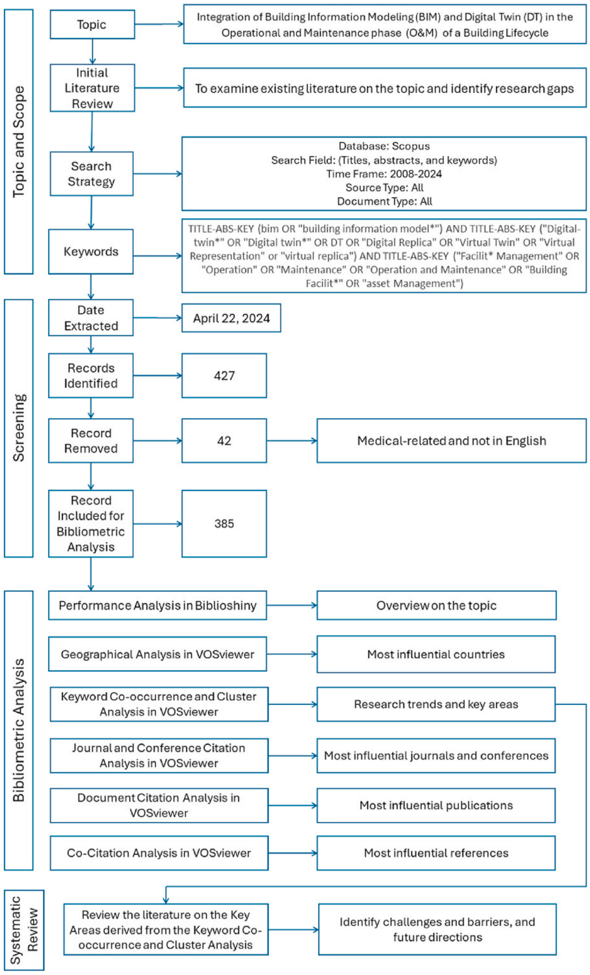

Fig. 1. Methodology Framework of the current research.

should be mentioned that DT is a well-known technology that promotes intelligent decision-making and enables instantaneous bidirectional integration of cyber-physical systems. Using low-cost and intelligent sensors, Internet of Things (IoT) devices, machine learning (ML), artificial intelligence (AI), blockchain, and big data analytics to assess the state and status of the assets, physical assets could be simply mapped to the platform that is digitally integrated through DT technologies [20,21]. In the end, DT has received a great deal of attention during the O&M stage, which has led to an abundance of scholarly articles examining this area within FM [22]. demonstrated the importance of the O&M phase of the building life cycle, which is costly and has received less research on the advantages of BIM than its applications in design and construction. Bibliometric research by Ref. [23] revealed issues with data interoperability but also offered the possibility that DT technologies could improve data integration throughout different FM phases. A scientometric analysis by Ref. [24] demonstrated the potential of massive data generated by the Internet of Things for FM. To effectively utilize digital technologies in smart FM [1], highlighted the need for additional research in AR-BIM integration, AI-driven prognostics during O&M, and DT-based infrastructure monitoring.

While BIM and DT technologies have shown significant potential in addressing inefficiencies in FM, particularly during the O&M phase, their practical integration and optimization remain underexplored. Existing research largely focuses on earlier lifecycle phases, overlooking the resource-intensive and complex O&M stage. Challenges such as data interoperability, stakeholder coordination, and the effective utilization of emerging technologies like AI and AR-BIM limit the adoption of smart FM practices and hinder seamless, data-driven asset management.

This study employs a comprehensive bibliometric and systematic review methodology to examine the scholarly ecosystem surrounding BIM and DT in the O&M phase. By addressing knowledge gaps, such as interoperability challenges and the need for advanced AI-driven tools, this research provides insights to support the adoption of smart FM practices through integrated, data-driven solutions. Additionally, it identifies trends, themes, and global contributions in the field, offering a detailed map of current knowledge and areas for future investigation. To achieve this, the study addresses the following research questions:

- What are the predominant keywords and scholarly themes surrounding BIM, DT, and O&M?
- What are the prominent countries, publications, and journals contributing to the field of BIM, DT, and O&M in construction studies?
- What future directions can be anticipated for BIM, DT, and O&M within construction research?

By quantitatively analyzing trends, topics, sources, and citations, this research not only enhances the existing body of knowledge but also suggests innovative directions for future studies into BIM and DT applications in the O&M phase of a building lifecycle.

2. Research methods and data collection

As shown in Fig. 1, this research examines the integration of BIM and DT in the O&M phase of a building lifecycle to understand and address existing research gaps. Bibliometric analysis and systematic literature review are employed as complementary methods to achieve this aim. Bibliometric analysis identifies key trends, collaborations, and research patterns, while the systematic literature review delves deeper into challenges, gaps, and opportunities in the field. Together, these methods provide a comprehensive approach to exploring the complexities of integrating smart technologies into the O&M phase.

This study introduces an innovative methodological framework by combining these methods to address the under-researched integration of BIM and DT in the O&M phase. Bibliometric analysis uncovers macro-level insights, such as research trends and collaborations, while systematic literature review offers micro-level analysis of barriers and future opportunities. This dual-method approach is uniquely suited to investigating the multifaceted challenges of the O&M phase, including data interoperability, stakeholder coordination, and prolonged lifecycle considerations [25,26]. The combined application of these methods not only addresses the research problem but also establishes a replicable framework for future interdisciplinary studies. Part of the bibliometric analysis involves a clear search strategy and data screening process, as outlined in Section 2.1.1. Once the data is collected, multiple analyses are conducted using tools such as VOSviewer and Biblioshiny, as described in Section 2.1.2. After identifying the key themes and areas of research, a systematic literature review is conducted to provide a deeper understanding, as discussed in Section 2.2. Section 3 discusses the results of the analysis, and the systematic literature review in Section 4 explores the key areas identified from the analysis to determine the challenges and barriers as well as future directions. Section 5 presents a roadmap of the future directions and concludes the study.

2.1. Bibliometric analysis

Bibliometric analysis is a method for analyzing large amounts of scientific data in a specific field using advanced quantitative and statistical methods [25,27]. Moreover, it can help in understanding the evolution of a particular field, uncovering new or trending areas of research, relevant publications, influential countries, authors, and institutions [25,28]. Bibliometric analysis mainly examines documents, authors, keywords, and sources using charts, network mapping, and clustering [1]. The development of scientific databases such as Scopus and Web of Science has made obtaining large amounts of bibliometric data easier. Additionally, bibliometric software like Gephi, Biblioshiny, Leximancer, and VOSviewer enables the efficient analysis and visualization of data, thus increasing interest in bibliometric [25].

2.1.1. Search strategy

This study utilized SCOPUS as the database to retrieve the literature through advanced keyword search. Scopus was selected since it is one of the most established scientific indexing and abstract databases. Its collection of literature is more comprehensive than other databases [1].

Fig. 2 shows the query used in Scopus. A comprehensive search was conducted on Scopus on April 22, 2024, using the title, abstract, and keywords fields. In the first part of the search query, "BIM"-related keywords were used. In the second part, "Digital Twin"-related keywords were used [1], and in the third, "operation and maintenance phase" related keywords were employed. The period for the search was left unrestricted, as well as the document type to obtain more comprehensive literature. However, medical-related subject areas were excluded to restrict the search to the engineering, construction, and environmental subject areas. Moreover, the search was restricted to include only English results. As a result, the search yielded 385 publications, with the first one dating back to 2008. Bibliometric analysis is then conducted on the resulting publications.

2.1.2. Tools for analysis

Several tools for bibliometric data analysis and visualization have been employed in research [29] VOSviewer, a free user interface-based software, is used in this study due to its versatility in analyzing literature from various sources [25,29. This study used VOSviewer to create, visualize, and analyze country, journal, and document maps based on citation, co-citation, and collaboration data, as well as keyword maps based on co-occurrence data and clustering analysis [28,30].

Moreover, Biblioshiny was used to obtain the performance data of the publications acquired from the search, such as the time-span of the research, number of sources and publications, number of authors, and annual scientific production, among others. Biblioshiny was used due to its user-friendly platform and its comprehensive visualization of publication performance data [28,31,32]. In addition, the world map diagrams were produced using Datawrapper, an online mapping tool, due to its user-friendly interface and versatility in displaying and translating data onto a world map [28]. Finally, SCImago Journal Rank (SJR) was used to obtain the impact factor of the top Journals in the field, because of its large journal database.

2.2. Systematic literature review analysis

A systematic literature review (SLR) helps establish a research context, define problems, support theories, and develop new inquiries by distinguishing between completed research and future needs, illustrating key findings [30,32]. An SLR gathers all relevant evidence systematically and evaluates it against specific criteria [32]. This method is designed to be replicable, scientific, and transparent, minimizing bias by conducting thorough searches of studies and maintaining a clear record of the reviewers' decisions, procedures, and conclusions [26]. As such, this study conducted SLR on the research themes that resulted from the clustering analysis.

3. Results and discussion

3.1. Performance analysis

As seen in Fig. 3, globally, there are 385 research documents on the use of BIM and DT in the O&M phase, spanning the last 17 years, with the first publication dating back to 2008. The first publication in this field, titled "Army BIM Pioneers," describes a project by the US Army Corps of Engineers (USACE) Seattle and Louisville districts, recognized for their work in the US Architecture, Engineering, and Operations (AECO) industry. This initiative employed BIM to virtually represent facilities' physical and functional characteristics throughout their lifecycle, demonstrating its potential for integrating virtual design, construction management, and geospatial data. The project included seven barracks buildings, with two campus-style complexes accommodating 300 and 239 people, and demonstrated the importance of standardized workflows and data management for BIM success. This early work not only defined BIM as a "virtual representation of physical and functional characteristics of a facility through its lifecycle," but also laid critical groundwork for advancing lifecycle management and operational integration—concepts that would later evolve into DT technologies [33].

However, progress in this field was initially slow. The second publication did not appear until four years later, in 2012, while the third in 2017. It was only in the last six years that the field experienced significant growth, with 98 % of the publications (n = 378) emerging during this period (see Fig. 4). Nearly 45 % of these were published in the last 16 months alone (January 2023 to April 2024). This shift exemplifies the accelerating interest in BIM and DT integration within the O&M phase, marking a rapid expansion following a slow start in its early years.

Enter query string

TITLE-ABS-KEY (bim OR "building information model*") AND TITLE-ABS-KEY ("Digital-twin*" OR "Digital twin*" OR DT OR "Digital Replica" OR "Virtual Twin" OR "Virtual Representation" or "virtual replica") AND TITLE-ABS-KEY ("Facilit* Management" OR "Operation" OR "Maintenance" OR "Operation and Maintenance" OR "Building Facilit*" OR "asset Management") AND (EXCLUDE (SUBJAREA,"NEUR") OR EXCLUDE (SUBJAREA,"PHAR") OR EXCLUDE (SUBJAREA,"PSYC") OR EXCLUDE (SUBJAREA,"IMMU") OR EXCLUDE (SUBJAREA,"AGRI") OR EXCLUDE (SUBJAREA,"MEDI") OR EXCLUDE (SUBJAREA,"BIOC")) AND (LIMIT-TO (LANGUAGE,"English"))

Fig. 2. Query String used in Scopus, showing the search strategy.

Fig. 3. Overview information of the publications under study.

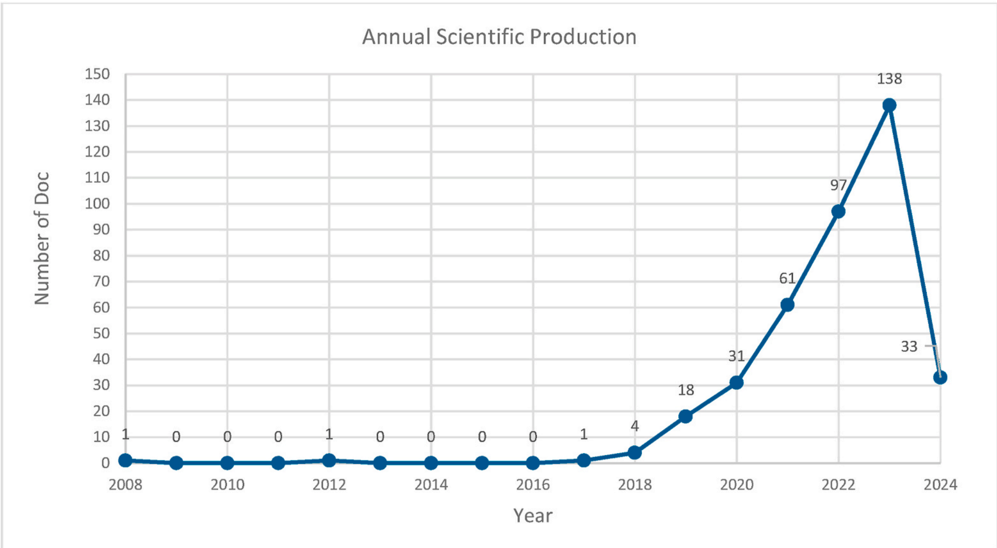

Fig. 4. Number of documents per year.

As shown further in Fig. 3, the annual growth rate of the field under study is 24.42 %, which demonstrates that this research area is highly active and can lead to innovation and advancements. This is further demonstrated in the document's average age of 2.05 years, which is the time it takes for a publication to be cited. Such a short average age shows that the field is evolving at a high speed. As for authors, there are 1175 authors in total, only 2.13 % of which have been sole authors, indicating that this field is highly collaborative with nearly 4 co-authors per document. Nearly a quarter (23.9 %) of the co-authorships are international, with the United Kingdom leading in international collaborations, particularly with China, later discussed further in Fig. 9 and Table 1. International collaboration is especially significant as it enhances the field's global impact by engaging wider audiences, fostering diverse perspectives, and strengthening the validation of findings, thereby boosting credibility.

Fig. 5 shows the total number of citations per year. The documents published in 2021 accumulated the highest number of citations

Table 1
Top ten countries by number of documents and number of citations.

No.	Country	Documents	Citations	Average Citation/Publication	Total link strength
1	Italy	73	737	10.096	15
2	China	56	1020	18.214	16
3	United Kingdom	53	2150	40.566	20
4	United States	39	698	17.897	18
5	Germany	32	393	12.281	5
6	Australia	24	1016	42.333	7
7	Denmark	14	199	14.214	8
8	Hong Kong	12	221	18.417	7
9	Norway	12	185	15.417	10
10	France	10	301	30.100	9

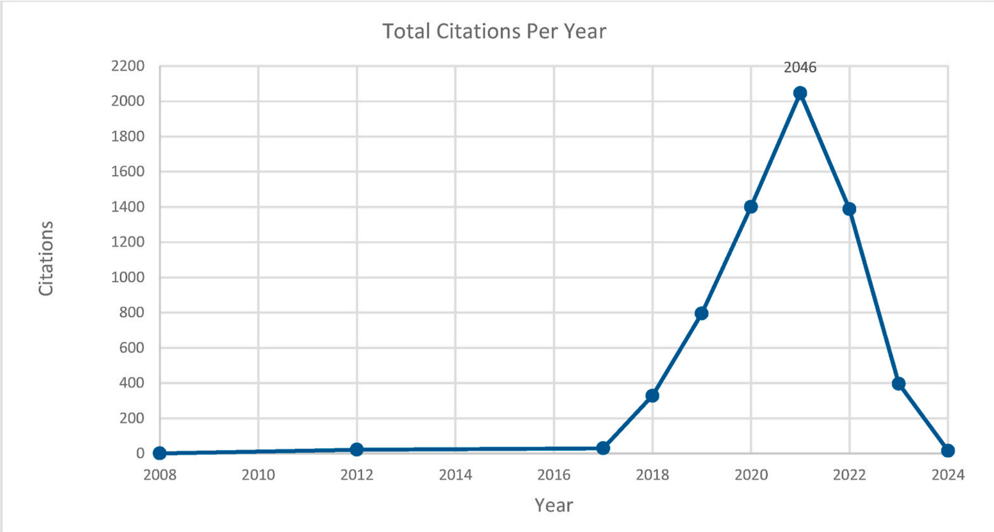

Fig. 5. Total number of citations per year.

of 2046. Evidently, five of the top ten cited articles were published in 2021 (see also Table 6 for more information).

The majority of the documents are conference papers, followed closely by article papers (Fig. 6). One reason for the conference type dominating is the novelty of the field, where conference papers enable researchers to quickly share preliminary findings. However, this also means that the majority of the publications might not be peer-reviewed, which shows a gap in the literature in terms of credibility and reliability of the data. Moreover, 10 % of the documents are review papers, which shows a growing interest in identifying new opportunities for research in this area.

3.2. Co-authorship

3.2.1. Geographical analysis of publications

Besides the field of BIM and DT integration in the O&M gaining interest over the years, this field has also garnered worldwide interest with 63 countries having published at least once. According to Fig. 7 and Table 1, Italy is the country with the most publications, followed by China and then the UK (73, 56, and 53 respectively). Notably, six out of the top ten countries come from Europe while two are from East Asia. This demonstrates that there are many regions where the research is lacking or of little interest such as the Middle East, Africa, South America, and the rest of Asia. This is evident in Fig. 7, where most of these region's countries have less than 10 publications (in yellow) or no publications at all (in gray).

Moreover, according to Fig. 8 and Table 1 the country with the most citations is the United Kingdom, followed by China and Australia (2150, 1020, and 1016, respectively). However, normalizing the number of citations per publication, Australia tops the list with nearly 42 average citations per publication.

Fig. 9 shows a network visualization of the countries. The size of the nodes indicates publication frequency and the links represent the connection strength (link strength) respectively. The same-colored countries belong to the same collaboration cluster, indicating

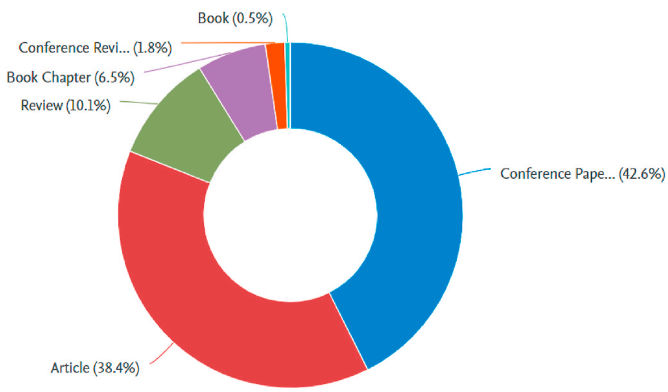

Fig. 6. Document by type.

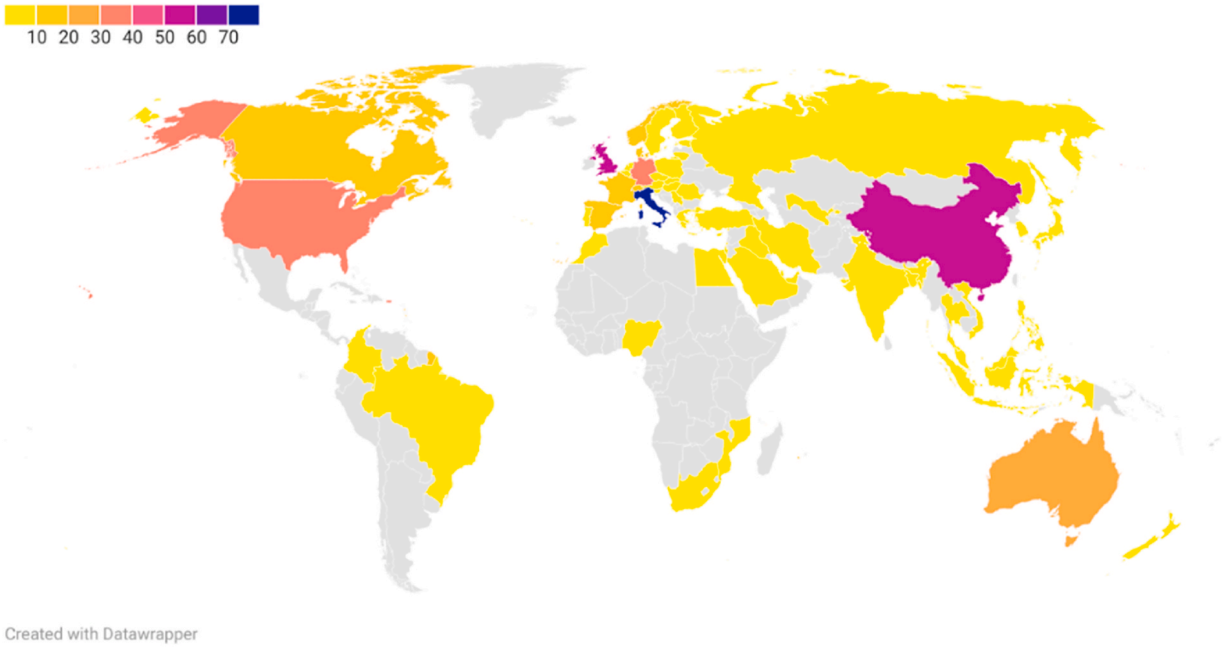

Fig. 7. Countries' scientific production.

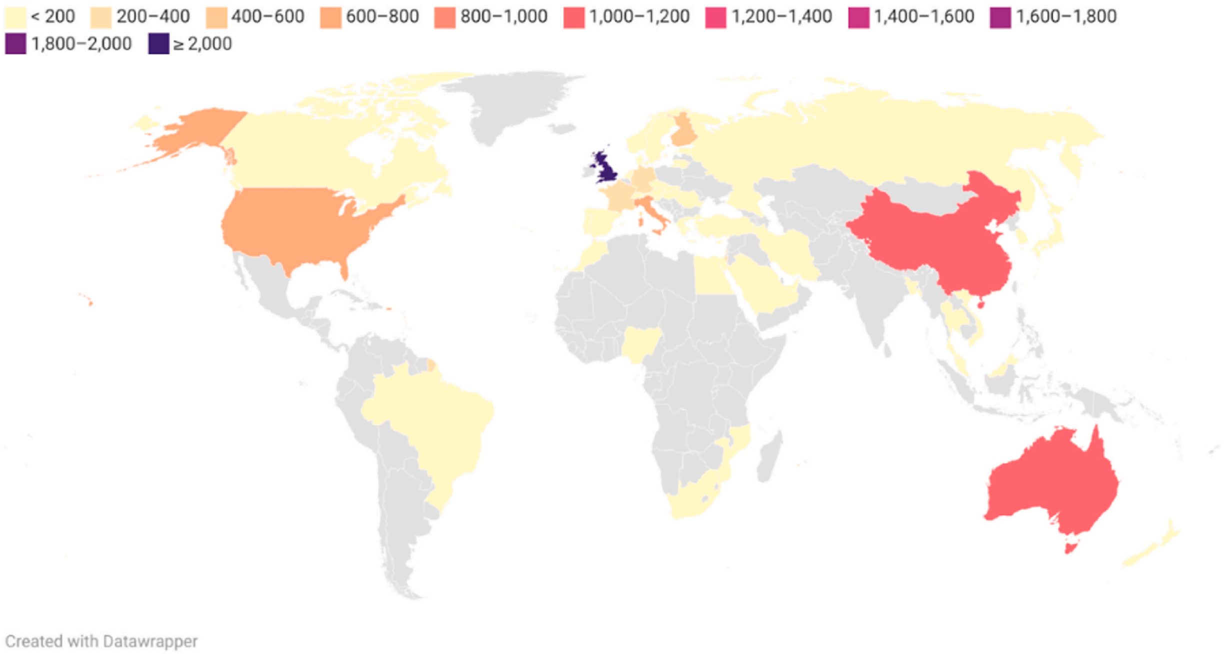

Fig. 8. Citations by country.

that the authors of the same publications associated with these countries frequently collaborate. The countries are divided into five clusters that illustrate the impact of geographical proximity and cultural similarity on authors' collaboration. The red, green, and yellow clusters consist of European countries as well as India and Brazil, the purple cluster consists of mostly East Asian countries, while the blue cluster consists of North American and Oceanic countries.

The link strength is useful in determining the extent and degree of a country's international research collaborations. Countries with high total link strengths engage in more international collaborations, indicating their strong global research networks [34]. The countries with the highest total link strength are the UK, the USA and China (see also Table 1). This is evident in Fig. 9 where the

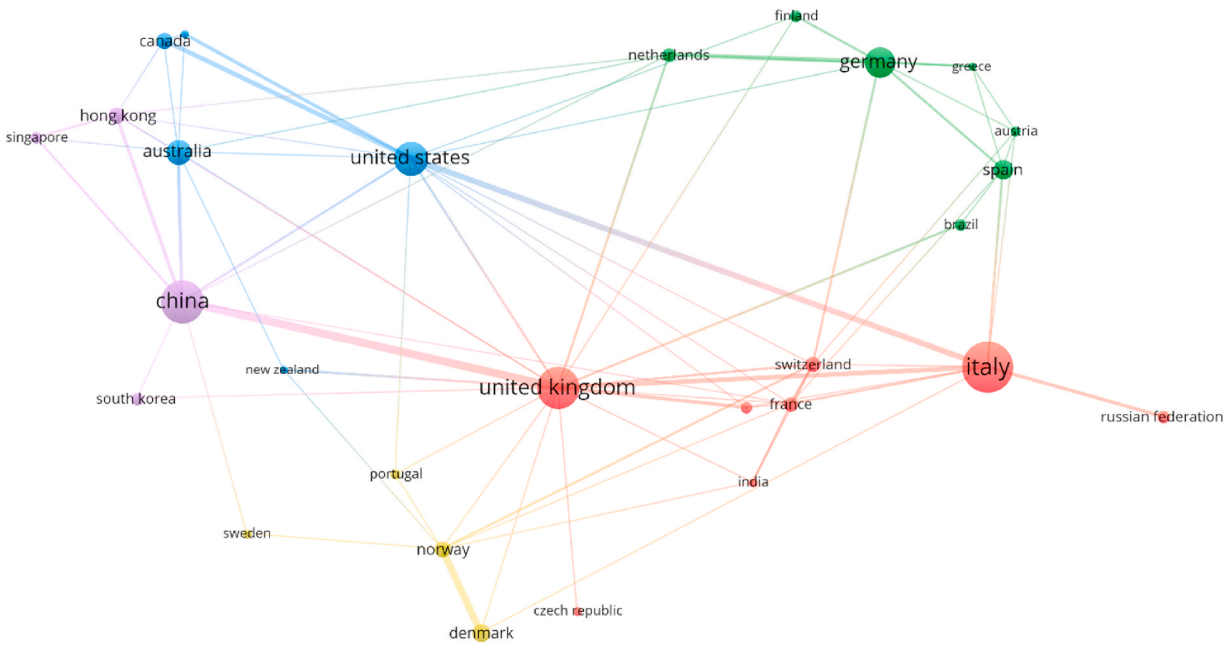

Fig. 9. Countries collaboration world map.

countries that have the highest numbers of the widest lines are the UK, China, and the USA, the widest one, in particular, is the one between the UK and China indicating a strong collaboration between them. The US and Italy also have a strong collaboration between them as with Norway and Denmark.

3.3. *Keyword Co-occurrence analysis*

Document data from Scopus was fed into VOSviewer to obtain all keyword co-occurrences. The threshold was set to 10 occurrences. Afterward, the keywords were cleaned of duplicates and redundancies. 55 keywords out of 2553 met the criteria, which were then mapped and visualized in Fig. 10. Each keyword is represented with a node whose size indicates the keyword's occurrences relative to each other. Furthermore, the 20 most popular keywords are shown in Table 2 by occurrences as well as total link strength.

The number of links and total link strength, as well as the proximity of the keywords to one another, show a given keyword's relatedness to other keywords. The strength of the link suggests the number of documents where two keywords appear together [1,30]. The word with the most occurrence is "digital twin," (199 occurrences) followed by "architectural design," (191) which has the highest total link strength (1065), emphasizing that most research is focused on architecture rather than other facets in the AEC industry such as engineering, infrastructure, structure, urban, etc. Many of the keywords are related to aspects of the O&M phase such as "life cycle", this is due to the O&M phase being the longest and costliest phase in a building's life cycle. Other keywords that relate to the O&M phase are "information management," "facilities management," "maintenance," "operations and maintenance," "asset management," and "energy efficiency," which is the result of good management of the O&M phase. Interestingly, "digital twin" has more occurrences than "building information modelling," this could be because the concept of DT is a BIM advancement that enables real-time motoring and smart feedback, which is much needed in the O&M phase. "Office building" is also a highly occurring keyword, this could indicate that the most researched building typology is office buildings. Similarly, "bridges," another highly occurring keyword, could be the most researched element within infrastructural research, due to the high need for ensuring their safety through regularly maintaining and inspecting them during the O&M phase.

The clustering of keywords was performed using VOSviewer, a bibliometric analysis software widely adopted for its ability to visualize and analyze networks of co-occurring keywords [35,36]. Specifically, the clustering process employed a modularity-based algorithm, which groups keywords into clusters by maximizing the modularity score—a measure of the density of connections within clusters compared to connections between clusters [37,38]. This approach ensures that the clusters are data-driven and reflect the underlying thematic structure of the dataset [36].

The selection of five clusters balances interpretability and thematic coherence, offering a meaningful synthesis of research trends. In Fig. 10, the colors represent the different clusters of keywords, which reflect distinct research themes. The first theme, Tech-Driven Sustainability, includes keywords related to smart facilities management and sustainability. The second theme, Digital Built Environment, focuses on GIS integration and digital urban systems. The third theme, Data-Driven Infrastructure Management, highlights structural health monitoring and asset management. The fourth theme, Digital Transformation in Heritage Maintenance, emphasizes historical building information modeling. Finally, the fifth theme, Digital Integration for Architectural Efficiency, centers around interoperability and smart building technologies.

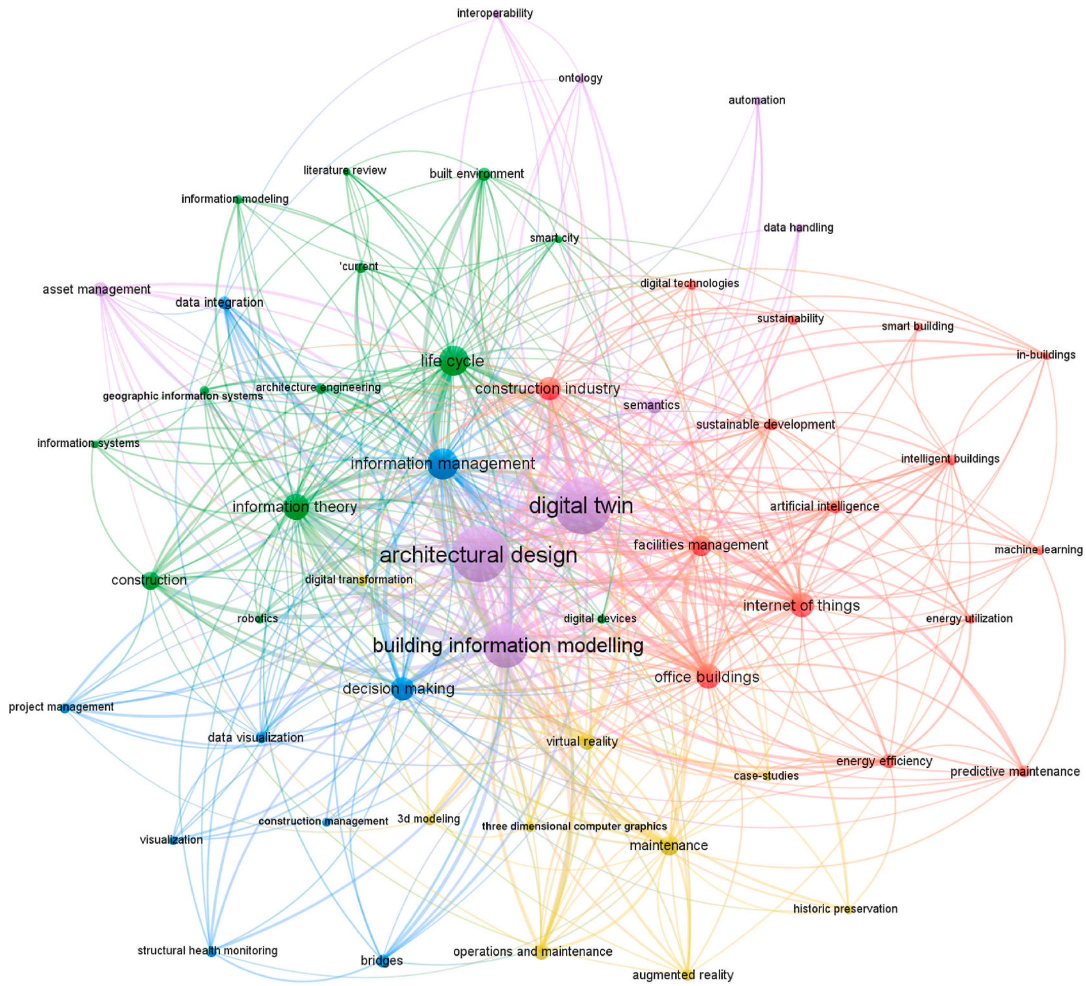

Fig. 10. Keyword co-occurrence network map.

Table 2
Top 20 keywords by occurrence.

No	Keyword	Occurrences	Total link strength
1	digital twin	199	851
2	architectural design	191	1065
3	building information modelling	142	825
4	information management	75	515
5	life cycle	69	444
6	information theory	58	389
7	office buildings	53	371
8	internet of things	51	309
9	construction industry	48	303
10	decision making	48	329
11	facilities management	41	270
12	maintenance	35	204
13	construction	33	188
14	operations and maintenance	26	162
15	virtual reality	26	164
16	semantics	25	155
17	asset management	23	126
18	energy efficiency	22	126
19	artificial intelligence	20	124
20	bridges	19	108

Building on the occurrences and total link strength highlighted in Table 2, Table 3 provides additional details about the clusters, including metrics such as their top keywords, the average publication year, average number of citations, and average normalized citations, which are discussed in the following paragraphs. Moreover, these thematic clusters are discussed in greater detail in Section 4, where their implications for the integration of BIM and DT in the O&M phase are further explored.

Fig. 11 visually demonstrates the average publication year of each keyword. The average publication year represents the arithmetic mean of the publication years for all documents associated with a given keyword. It provides a quantitative measure to identify the

Table 3
The five clusters and their keywords.

Keyword	Links	Total link strength	Occurrences	Avg. publication year	Avg. citations	Avg. normalized citations
Cluster 1 (Red) - Tech-Driven Sustainability: Smart Facilities Management (SFM)						
artificial intelligence	40	122	20	2022.45	17.85	2.55
construction industry	52	298	48	2021.92	39.38	1.73
digital technologies	37	79	13	2021.85	45.00	1.85
energy efficiency	40	125	22	2022.59	13.86	1.89
energy utilization	32	77	12	2022.67	8.75	0.86
facilities management	50	263	41	2022.39	15.32	1.48
in-buildings	27	68	10	2022.70	6.90	1.12
intelligent buildings	38	117	14	2022.07	25.00	1.93
internet of things	51	304	51	2022.22	40.37	1.90
machine learning	32	72	12	2022.42	17.75	2.37
office buildings	51	361	53	2021.89	22.85	1.31
predictive maintenance	23	77	16	2021.75	32.06	2.01
smart building	28	52	11	2022.36	11.64	0.77
sustainability	31	69	13	2022.38	21.69	1.79
sustainable development	39	117	16	2022.06	20.25	1.30
Cluster 2 (Green) – Digital Built Environment: Geographic Information Systems (GIS) Integration						
’current	38	96	15	2022.73	21.67	1.40
architecture engineering	33	87	14	2022.29	18.57	2.04
built environment	35	125	19	2022.11	19.74	1.55
construction	45	187	33	2021.94	37.15	2.05
digital devices	37	80	11	2022.36	8.27	0.83
geographic information systems	36	103	12	2022.42	16.33	1.56
information modeling	29	70	11	2021.73	7.82	0.97
information systems	30	75	10	2021.80	45.80	1.94
information theory	53	380	58	2022.17	20.69	1.65
life cycle	52	434	69	2022.12	32.65	1.40
literature review	29	61	10	2022.10	44.10	3.08
robotics	29	63	10	2021.60	5.30	0.27
smart city	37	82	10	2021.80	44.50	2.25
Cluster 3 (Blue) - Data-Driven Structure and Infrastructure Management						
bridges	36	108	19	2022.16	7.84	1.00
construction management	23	44	11	2022.09	14.82	0.97
data integration	37	126	19	2022.53	26.32	2.25
data visualization	37	107	17	2022.59	18.41	1.26
decision making	49	318	48	2022.17	20.52	1.53
information management	54	499	75	2021.97	38.29	1.79
project management	30	95	14	2021.29	75.36	2.27
structural health monitoring	28	80	15	2022.80	2.13	0.54
visualization	27	62	11	2021.55	8.91	0.96
Cluster 4 (Yellow) - Digital Transformation in Heritage Maintenance: Historical Building Information Modeling (HBIM)						
3d modeling	39	90	14	2022.14	8.29	0.51
augmented reality	31	96	16	2021.69	25.19	1.85
case-studies	33	75	12	2022.75	8.25	0.72
digital transformation	37	85	14	2021.50	13.79	1.71
historic preservation	28	63	12	2022.67	7.83	0.60
maintenance	46	200	35	2021.83	17.86	0.75
operations and maintenance	38	156	26	2022.23	19.58	0.82
three-dimensional computer graphics	30	77	13	2021.85	18.92	1.13
virtual reality	45	157	26	2022.04	13.31	1.82
Cluster 5 (Purple) - Digital Integration for Architectural Efficiency: Semantic Interoperability						
architectural design	54	1036	191	2022.05	18.72	1.23
asset management	32	110	23	2021.57	28.26	1.25
automation	26	51	11	2022.55	12.82	1.13
building information modelling	54	805	142	2022.15	16.14	1.13
data handling	33	63	12	2022.33	5.17	0.71
digital twin	54	832	199	2021.94	22.94	1.33
interoperability	24	55	11	2022.18	8.27	0.74
ontology	30	72	12	2021.83	14.58	1.77
semantics	43	152	25	2021.56	32.44	1.43

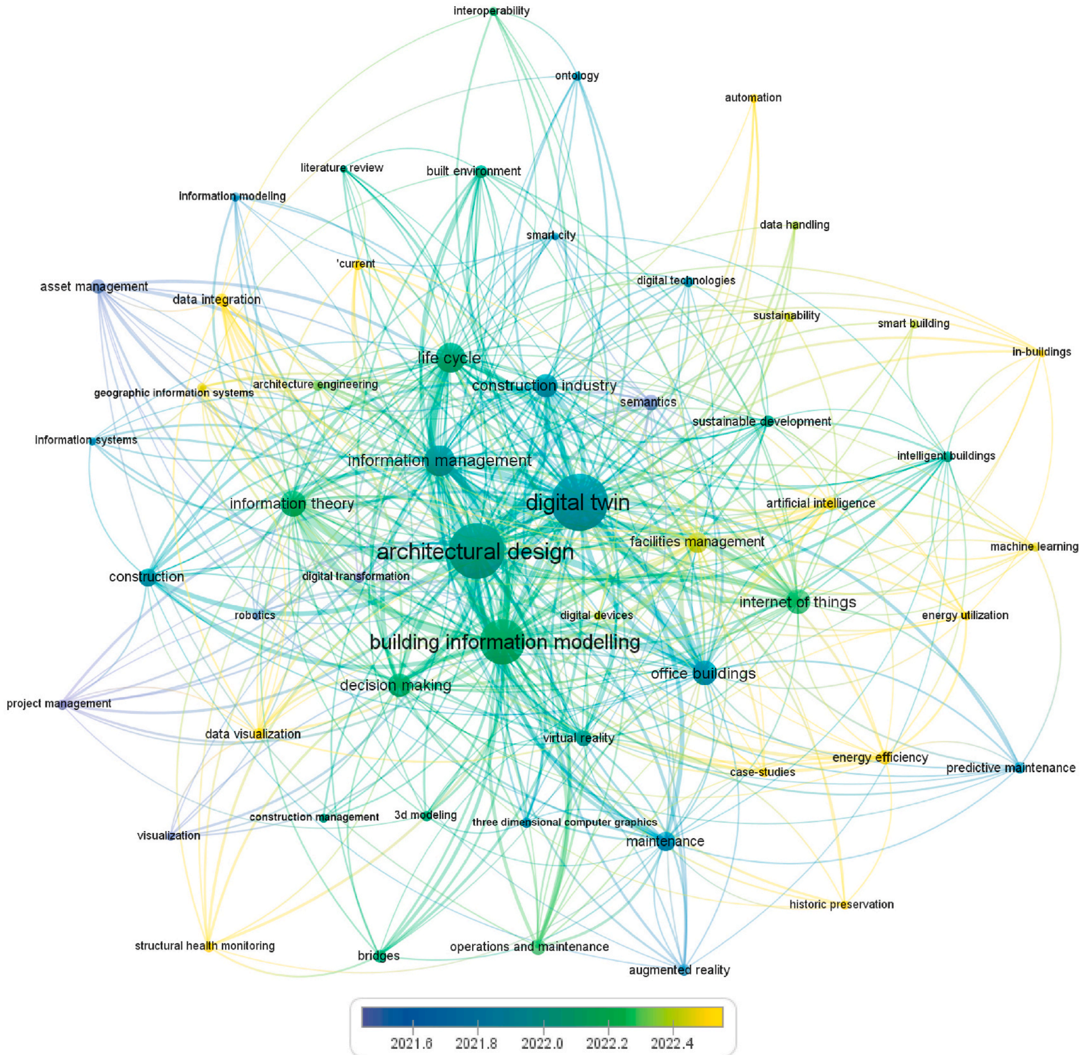

Fig. 11. Keyword average publication per year network map.

recency of research activity [34]. The more yellow the keywords are, the more recent they are in terms of research interest, or emerging research. While the keywords that are more in blue signify more mature or well-established research areas. For example, "energy efficiency," "predictive maintenance," "automation," "artificial intelligence," "machine learning," "data visualization," "historic preservation," and "structural health monitoring," are among the trending research topics in the field under study. However, the more recent the keywords are the lower their occurrence, indicating that more research is needed for them. In terms of the clusters, the cluster with the most recent keywords is the red cluster which corresponds to the "Tech-Driven Sustainability" research theme indicating that it is the most actively evolving or trending research area. Overall, the average publication year of all the key areas is 2022, indicating an emerging interest in the field of BIM and DT in the O&M phase. This average publication year signifies the innovative and transformative nature of the field, which can be expected to evolve and advance rapidly in the coming years.

Along with Table 3, Fig. 12 visualizes the average normalized citations of the keywords. [28]. The metric represents the average normalized citation count of documents containing a specific keyword or term. Normalizing citations accounts for the fact that older documents have had more time to obtain citations. Thus, the normalized number of citations ($C_{normalized}$) for a document is calculated as:

$$C_{normalized} = \frac{C_{document}}{Avg(C_{year})}$$

Where, $C_{document}$ is the number of citations of the document, and AVG (C_{year}) is the average number of citations for all documents published in the same year included in the dataset provided to VOSviewer. Then, to calculate the average normalized citation count for a keyword, the normalized citation counts of all documents containing that keyword are averaged [34].

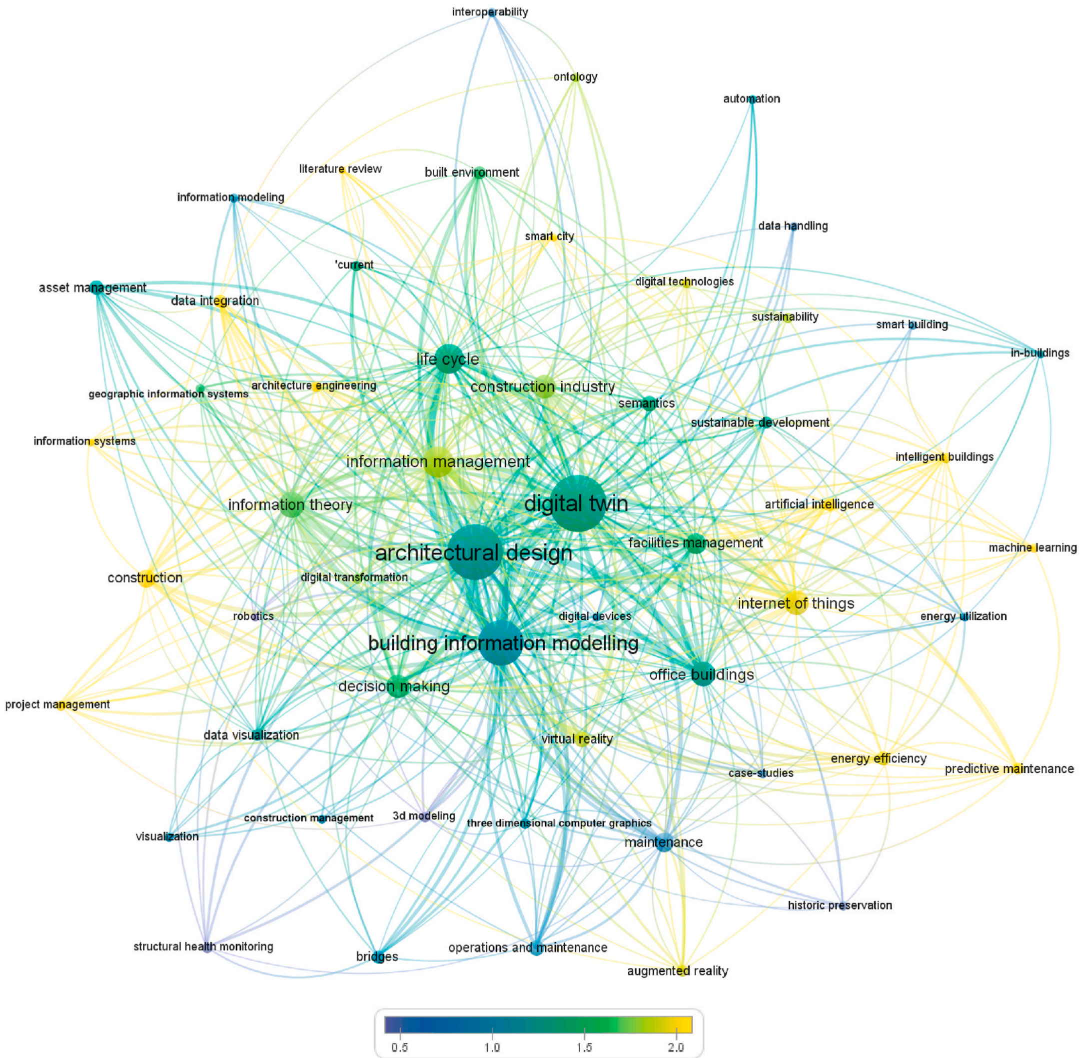

Fig. 12. Keyword average normalized citation map.

The three keywords with the highest averaged normalized citations values, as shown in Table 3, are 'literature review' (3.08), 'artificial intelligence' (2.55), and 'machine learning' (2.37), respectively. AI and machine learning play a critical role in the O&M phase by driving advancements in automation and decision-making through effective data utilization. Another notable keyword, 'predictive maintenance' (2.01), is both highly cited and relatively recent. This approach offers significant benefits in the O&M phase, such as minimizing unplanned failures, reducing maintenance costs, and enhancing the comfort and safety of occupants or workers. However, implementing predictive maintenance presents challenges, including connecting physical assets, extracting valuable data,

Table 4
Top ten journals in the field of BIM, DT, and O&M.

No.	Source	Total Publications	% of total publications	Total Citations	IF 2024
1	Applied Sciences (Switzerland)	13	3.38	322	2.7
2	Automation in Construction	18	4.68	1503	10.3
3	Buildings	19	4.94	404	3.8
4	Energies	7	1.82	79	3.2
5	Energy and Buildings	7	1.82	200	6.7
6	Frontiers in Built Environment	4	1.04	135	3.0
7	IEEE Access	5	1.30	391	3.9
8	Journal of Building Engineering	4	1.04	376	6.4
9	Journal of Information Technology in Construction	4	1.04	176	NA
10	Sustainability (Switzerland)	9	2.34	272	3.9

and developing accurate predictive algorithms [39]. These algorithms rely on AI and machine learning techniques, presenting a clear opportunity for future research to refine these technologies and their applications. Other highly cited keywords include 'smart city' (2.25), 'data integration' (2.25), and 'project management' (2.27), highlighting their importance in the field. Conversely, keywords with the lowest normalized citation values, such as 'robotics' (0.27), '3D modeling' (0.51), and 'structural health monitoring' (0.54), indicate areas requiring further research to bridge existing gaps and expand their application in the O&M phase.

3.4. Citation analysis

3.4.1. Journal and conference citation

Table 4 and Table 5 show the top ten journals and conferences respectively in the field of BIM and DT in the O&M phase. The journal with the most publications is *Buildings* (19 documents) with an impact factor of 3.8, followed by *Automation in Construction* (18 documents, IF 10.3), and *Applied Sciences* (13 documents, IF 2.7). The journal with the most cited papers is *Automation in Construction* with 1503 citations, while the second most cited journal, *Buildings*, has a significantly lower number of citations of 404. This could be because *Automation in Construction* is a more specialized journal on a certain topic, which is automation in construction, while *Buildings* encompasses more research fields in construction. The journal with the highest impact factor as of 2024, is *Automation in Construction*. Overall, *Automation in Construction* seems to be the most impactful journal in this field. As for conferences, the top three conferences in terms of total publications are the *International Archives of The Photogrammetry, Remote Sensing and Spatial Information Sciences* (which is also the most cited), *IOP Conference Series: Earth and Environmental Science*, and *Proceedings of the International Symposium on Automation and Robotics in Construction*.

3.4.2. Document citation

Table 6 displays the most cited publications in the field of BIM and DT utilization in the O&M phase. These publications are the most influential in the field. Examining the documents closely reveals that most of these publications concentrate on the theoretical aspects of BIM and DT in features of the O&M phase. This once again indicates that the research in this field is in its early stages and is not fully developed, which shows a gap in the literature, where real-life case studies and practical research are rare. The top cited document is [40], which has been cited 522 times, nearly double that of the second most cited document. This article reviewed the current state of BIM application during the construction stage, investigated the components and perceived capabilities of DTs across a broad range of engineering domains, and highlighted current gaps and potential areas for further study. Moreover, the article explained how to transition from a BIM to DT, which offered more opportunities in the IoT and AI intersection via semantic models. Finally, this article argued that for BIM to respond to newer, more integrated approaches at the building and city levels, a Digital Twin paradigm must be implemented [40]

The second most cited document is [13] who investigated the use of the DT in building life cycle management, exploring its advantages and disadvantages. Over 25,000 sensor readings were gathered and analyzed to generate a DT of an existing office building facade portion. This was done to highlight the method of implementation, show the benefits of DT, and expose some of the technical weaknesses in the current IoT systems utilized for this purpose. The findings revealed that the DT offered insights into the building's operational efficiencies and potential areas for improvement, leading to better management and maintenance strategies. According to the authors, future research should investigate the applications of DTs for building interiors rather than just the exterior [13]. Even though this paper does investigate a real-life case study, the specific quantitative results detailing the outcomes of the sensor readings and the improvements gained from implementing the DT are not explicitly detailed. Notably, the two aforementioned articles are among the highly cited references by the 385 documents obtained from Scopus for this study (see also Section 3.4.3). This illustrates the noteworthy influence that these two articles have in the field.

3.4.3. Document Co-Citation

This section discusses the top-cited references among the documents obtained from Scopus in the field under study. As shown in Table 7, the most cited reference is [13] with 8.57 % of the documents citing it. It is also the second most cited document among the

Table 5
Top ten conferences in the field of BIM, DT, and O&M.

No.	Source	Total Publications	% of total publications	Total Citations
1	CEUR Workshop Proceedings	5	1.30	6
2	International Archives of The Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives	12	3.12	41
3	IOP Conference Series: Earth and Environmental Science	11	2.86	18
4	IOP Conference Series: Materials Science and Engineering	3	0.78	20
5	Journal Of Physics: Conference Series	3	0.78	4
6	Lecture Notes in Civil Engineering	7	1.82	12
7	Proceedings Of SPIE - The International Society for Optical Engineering	5	1.30	5
8	Proceedings of the European Conference on Computing in Construction	8	2.08	7
9	Proceedings of the International Symposium on Automation and Robotics in Construction	11	2.86	8
10	WIT Transactions on The Built Environment	3	0.78	8

Table 6
Top ten cited documents.

No.	Author and Year	Title	Citations
1	[40]	Towards A Semantic Construction Digital Twin: Directions for Future Research	522
2	[13]	Digital Twin: Vision, Benefits, Boundaries, And Creation for Buildings	284
3	[41]	Digital Twin Application in The Construction Industry: A Literature Review	248
4	[42]	Construction With Digital Twin Information Systems	235
5	[43]	A BIM-Data Mining Integrated Digital Twin Framework for Advanced Project Management	226
6	[44]	Digitisation In Facilities Management: A Literature Review and Future Research Directions	179
7	[45]	Digital Twin and Its Implementations in The Civil Engineering Sector	172
8	[46]	From BIM To Digital Twins: A Systematic Review of The Evolution of Intelligent Building Representations in the AEC-FM Industry	164
9	[47]	Digital twin aided sustainability-based lifecycle management for railway turnout systems	151
10	[48]	Differentiating Digital Twin from Digital Shadow: Elucidating A Paradigm Shift to Expedite a Smart, Sustainable Built Environment	146

Table 7
Top ten cited references.

No.	Cited reference	Title	Citations	% of total publications	Links	Total link strength
1	[13]	Digital Twin: Vision, Benefits, Boundaries, And Creation for Buildings	33	8.57	100	123
2	[49]	Rugged LV Trench IGBT with Extreme Stability in Continuous SOA Operation: Next Generation LV Technology at Hitachi ABB Powergrids	23	5.97	2	15
3	[40]	Towards A Semantic Construction Digital Twin: Directions for Future Research	16	4.16	53	66
4	[50]	Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison	14	3.64	32	58
5	[44]	Digitisation In Facilities Management: A Literature Review and Future Research Directions	13	3.38	36	51
6	[51]	A Review of Building Information Modeling (BIM) And the Internet of Things (IoT) Devices Integration: Present Status and Future Trends	11	2.86	61	40
7	[52]	Digital Twin in Manufacturing: A Categorical Literature Review and Classification	10	2.60	43	42
8	[16]	Bim for Facility Managers	10	2.60	39	26
9	[53]	Digital Twin: Enabling Technologies, Challenges and Open Research	10	2.60	37	41
10	[54]	Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, Transdisciplinary Perspectives on Complex Systems	10	2.60	35	31

385 ones obtained from Scopus (see also Section 3.4.2 as it discusses the article in more detail). It also has the most links of 100, meaning that it has been cited together (co-cited) with 100 other references. It also has the highest link strength of 123, indicating its influence among scholars in the studied field. The second most cited reference is [49], a conference paper that aimed to present an improved trench gate Insulated Gate Bipolar Transistor (IGBT), which is used for switching electronic devices, in simple terms [49]. However, this paper is not among the most integrated in the network of references as it is co-cited with only 2 other references. This could be due to the highly specialized topic it presented. The third most cited reference is [40] with 16 citations and 53 co-citations. Interestingly, it is the most cited document among the 385 ones obtained from Scopus, signifying its high influence in the field.

Conversely, among the least cited references is a book chapter in ref. [50] which discussed the development of the DT concept, its use throughout a product lifecycle and its role in "Systems Engineering". The chapter emphasized DT's ability to address human errors and discussed both challenges and opportunities. The authors concluded by discussing NASA's current work with DT [54].

4. Research themes

4.1. Tech-Driven Sustainability: smart facilities management (SFM)

This key area focuses on technology integration, innovative strategies, and sustainable user-centric buildings. This is evident in the corresponding cluster's keywords such as “artificial intelligence”, “digital technologies”, “facilities management”, “sustainability” and “smart building”, among other keywords.

To improve occupants' living standards using information and communication technology, the construction industry needs to understand the concepts of smart building (SB) and smart facilities management (SFM) [55]. SB is concerned with the building's operation and maintenance (O&M) stage rather than its design. According to Ref. [56] a building must accomplish its intended function as well as adapt and vary from its planned design to truly attain an SB. Because SFM adoption is the cornerstone of the SB goals and O&M accounts for approximately 60 % of the overall cost borne by owners [55,57], effective FM is therefore critical to attaining the SB goals. Smart building refers to a high degree of building operating efficiency enabled by digital technologies, whereas smart FM explains how to employ digital tools to optimize the management process [58]. To accomplish the objectives of smart buildings, smart facilities management makes use of innovative, modern information technology and machinery. SFM is providing owners and occupants with increased visibility, actionable insights, and cost savings thanks to the adoption of BIM, DT, IoT, AI, augmented reality (AR), virtual reality (VR), mixed reality (MR), Construction Operations Building Information Exchange (COBie), and data analytics technologies [13,59]. There is not much research on smart FM, despite the FM business using smart technologies much more in the past ten years.

4.1.1. Challenges and barriers

When choosing to integrate DTs in smart buildings at the facility management level, there are obstacles to overcome despite the tremendous potential of BIM and DTs for smart buildings. The lack of a systematic and thorough reference model, real-time data integration, the complexity and uncertainty of real-time data, and real-time data visualization are the four main challenges associated with DTs for smart buildings at the facility management stage, according to Ghansah's study [60]. Another difficulty is that to produce better results, most BIM technologies in SFM require high bandwidth, low latency connections, and cloud computing [55]. However, the current wireless networks (e.g., Wi-Fi, 4G, 3G) that support these functions present several obstacles to the wider adoption of these innovative technologies. These include the lack of bandwidth availability for real-time analysis due to the integration of technologies such as BIM and AR/VR/MR, which is made worse by inconsistent network performance [61]; the inability of current networks to meet low latency requirements for cloud-based systems and immersive technologies [62]; the proliferation of IoT devices increases cybersecurity risks as networks struggle to handle encrypted data volumes securely [63]; rigid network structures impede customization for a variety of SFM applications, while scalability issues arise with the growing number of IoT devices within defined [64].

4.2. Digital Built Environment: geographic information systems (GIS) integration

This key area focuses on the informational and digital aspects of the urban environment. This is evident in the corresponding cluster's keywords such as "digital devices", "geographic information systems", "information modeling", "life cycle" and "smart city", among other keywords.

DT and BIM in smart cities combine Geographic Information Systems (GIS) and Internet of Things (IoT) to create dynamic, three-dimensional models of urban environments. This has allowed BIM to advance beyond the building level to the city level, resulting in a concept known as City Information Modeling (CIM), which combines GIS data, BIM, and the use of IoT sensors to create Digital Twins. These models improve decision-making and O&M management across various urban systems by simulating reality in real time and enabling dynamic virtual-real interaction [29,65-69]. Integrating GIS and BIM has a lot of advantages such as improving data accuracy and reducing risks and inefficiencies at the urban level in city operations and maintenance. For example, integration has been shown to increase data accuracy by 59 %, enhance data retrieval efficiency by 63 %, and collaboration by 62 % [29]. Furthermore, Avezbaev [70] claims that smart cities can save up to 30 % of electricity, 15 % of water consumption, and 20 % of the time people spend in traffic. Beyond individual buildings, DT applications have been investigated at the community and city scales, focusing on enhancing building energy management, urban planning, and disaster response [46,69,71].

Evangelou et al. [65] proposes a methodology for transitioning from static BIM data to dynamic DTs, with a focus on lifecycle management of the built environment. Their findings advocate for the use of real-time sensor data to improve the functionality and responsiveness of DTs. Shahzad et al. [72] examines the literature and conduct interviews with experts to address the operational challenges and potential applications of DTs in asset management, emphasizing the need for data-centric technologies to enhance decision-making processes within built environments. They emphasize the significance of data interoperability and the incorporation of digital technologies in improving the operational phase of asset management. Agostinelli's [66] research focuses on creating a digital framework for urban security and facility management employing City DTs. The study combines artificial intelligence and image recognition systems, predictive maintenance systems, and data analytics to improve urban security and maintenance efficiency. The findings show that the use of AI and machine learning can automate facility management tasks, lower operational costs, and improve operational efficiency. This study suggests that DTs can go beyond traditional city management to improve urban security and provide comprehensive management for smarter, safer, and more efficient cities [66]. However, in the literature, it is difficult to find real-world case studies, multiple studies have proposed conceptual DT frameworks for city O&M management, this is also highlighted in Deng et al.'s review [46] Therefore, researchers need to evaluate existing DTs to understand their actual efficiencies, rather than relying solely on theoretical models.

4.2.1. Challenges and barriers

Further challenges and barriers exist. The primary challenge in advancing DT technology in smart cities is the integration of complex and heterogeneous data sets across different technology platforms [69,72]. Establishing universal standards for data interoperability and security is crucial to overcome this barrier [69,72]. Additionally, the adaptation of legal frameworks to accommodate new technologies and the management of intellectual property rights within these digital environments remain significant obstacles. Ensuring data privacy and securing cyber environments are critical as the deployment of DTs involves handling substantial amounts of sensitive information [65,72]. Furthermore, the necessity for systemic cultural change and workforce upskilling to adapt to new technological demands complicates the implementation process [72].

4.3. Data-driven structure and infrastructure management

This key area focuses on the management of structural and infrastructural aspects of construction. This is evident in the corresponding cluster's keywords such as “bridges”, “construction management”, “decision making”, “project management” and “structural health monitoring”, among other keywords. Recent advances in DT and BIM have had a significant impact on civil infrastructure management, especially in bridge engineering and structural health monitoring. Mohammadi et al. [73] worked on using Terrestrial Laser Scan (TLS) to generate Bridge Information Modeling (BrIM) data for improving Bridge Management Systems (BMS). The BMS incorporated BrIM geometrical and non-geometrical data on the bridge elements, as well as a requirement-driven framework for a condition assessment model for prioritizing bridge elements based on their health status. The study then implemented a Decision Support System (DSS) to optimize corrective measures and budget allocation. This approach was validated by conducting a case study on the Werrington Bridge in Australia, illustrating the potential for objective management practices. This study's findings confirm the reliability of "BrIM-oriented BMS" implementation as well as DSS integration. According to the authors, a future step is to employ AI and IoT sensors to create dynamic bridge DTs [73]. However, the study could have also provided more numerical information on the cost efficiency before implementing the framework and after implementing it, to understand the improvement in the context of what already exists.

Kaewunruen et al. [74] investigated the use of DTs for risk-based bridge inspection and maintenance using data from a bridge in China. Their research focused on the transition from traditional to digital methods, specifically the use of BIM to improve risk inspection models. This included real-time monitoring via sensors, computer simulation, and a three-dimensional model for easier risk management, planning, and tracking. The integration of the "BIM + bridge risk inspection model” aimed to increase the efficiency of bridge maintenance and risk management [74]. Hakimi et al. [75] proposed a comprehensive framework for managing civil infrastructures across their lifecycle by combining DT, BIM, IoT, and AI with data fusion. The study identified challenges such as data integration difficulties and the need for multilayer data fusion to optimize infrastructure management during the O&M phase and optimize stakeholder decision-making processes [75]. A subsequent study can implement and test the proposed framework on a real-life case study.

4.3.1. Challenges and barriers

Implementing DT and BIM in civil infrastructure management faces several challenges, including the complexity of integrating multisensory data and selecting algorithms, ensuring high data quality, and technological constraints [75,76]. Achieving two-way data flow, where real-time data updates the DT and vice versa is still lacking in implementation [76]. Moreover, applying theoretical knowledge to practical real-life scenarios is challenging. Additionally, these technological advancements face significant cost and return on investment barriers, requiring extensive case studies to validate their long-term benefits [75,76]. However, there is a noticeable lack of DT real-world applications for structural health monitoring (SHM) of civil infrastructures and infrastructure management in general. This is mainly due to the proprietary nature of the algorithms, modeling methods, and sensor integration techniques used to create DTs, which typically leads companies to protect these innovations as intellectual property. This prevents the widespread dissemination of proven, real-world applications. There should be a balance established between intellectual property protection and collaborative efforts to encourage the widespread implementation of practical applications [76]. Another major challenge is quickly modeling complex bridge structures, which requires significant human resources and time, emphasizing the need for more efficient modeling techniques [74]. Furthermore, the knowledge and skill gaps are significant barriers to effective DT implementation in infrastructure management. Therefore, appropriate training and effective knowledge transfer are critical [75].

4.4. Digital Transformation in Heritage Maintenance: Historical Building Information Modeling (HBIM)

This key area primarily relates to the integration of digital technologies into maintenance and operations practices, and historic preservation efforts within the built environment. This is evident in the corresponding cluster's keywords such as “digital transformation”, “operation and maintenance”, “historic preservation”, “augmented reality” and “3d modeling”, among other keywords. Lack of documentation and as-built information is a serious problem for heritage assets undergoing restoration, which can result in ineffective project management, greater costs, and longer restoration times. To solve these issues, a sophisticated documentation approach for historic buildings is used, resulting in a geometrical model that houses all the data in a single database and efficiently supports the restoration process—a critical component of the O&M phase of historic buildings [77]. Heritage building information modeling (HBIM) was first proposed by Murphy et al. [78], who also described the potential of BIM approaches in historic contexts [77,78]. A historical building's HBIM can offer the following benefits: (i) a thorough survey and parametric modeling on the geometrical aspect; (ii) information on the attributes, materials, and relationships of the sub-elements; and (iii) potential deformations and changes throughout time [79]. Additionally, the integrated 3D model and its historical semantic data are stored in the HBIM system, which serves as the management system for heritage structures.

According to Heesom et al. [80], the HBIM concept has shown promise in recent applications for integrating historical data, including documents, structural details, monitoring data, and the current condition of buildings within a 3D environment. This has made it easier to model, document, conserve, and classify historical architectural elements [81]. For example, HBIM can be helpful in the creation of 3D parametric models and capture of intricate historical geometry through photogrammetry and laser scanning techniques [77,82]. Furthermore, DT technology is employed for data storage and graphical representation—tasks that are critical for the protection of built cultural heritage (BCH) and help to expand knowledge by documenting any changes that take place. To gather geometrical data and information from non-destructive testing (NDT) that is helpful for the real-time assessment of potential changes in the conditions of structures, HBIM models are frequently used as digital replicas inside the DT implementation [83]. HBIM is seen as a promising resource for planned conservation of historical assets because of its capacity to archive and organize all the information about a building [84].

4.4.1. Challenges and barriers

Though it has many advantages, the use of HBIM for reconstruction planning and FM activities, as well as for integrating semantic information specifically related to heritage management and lifecycle data at a different period with complex geometries, is hardly ever investigated [77]. Because most cultural heritage professionals lack information technology training and expertise, there is a lack of clear, precise, and shared regulatory references and guidelines, which contributes to the limited use of Historic BIMs (HBIMs). On the other hand, applying BIM to heritage assets can present challenges [84]. However, there are still several obstacles that must be overcome for the integration and transformation of various environments. These include addressing the regular and complex structures of the environments in the scan-to-HBIM and HBIM-GIS integration, implementing interactive parametric design between computer graphics and HBIM, and preventing information loss during the model transfer [79].

4.5. Digital Integration for Architectural Efficiency: semantic interoperability

This key area primarily relates to the integration of digital technologies, such as BIM, with asset management practices and architectural design within buildings. This is evident in the corresponding cluster's keywords such as “architectural design”, “asset management”, “building information modelling”, “digital twin” and “semantics”, among other keywords. Throughout its lifecycle, smart buildings use intelligent technologies and BIM to achieve FM that is comfortable, sustainable, and efficient [85]. This cluster suggests that establishing smart FM requires real interconnection. Semantic models, or higher-level abstractions, are still seen as a useful tactic for handling heterogeneity in data and systems. In this context, "semantic interoperability” refers to the capacity of different agents, services, and applications to exchange vast quantities of information, expertise, and context awareness for the building's advantage [86-88]. As it guarantees that data maintains its intended semantics despite variations in data formats, structures, or vocabularies, this idea is essential for facilitating successful communication and collaboration among heterogeneous systems [89]. During the O&M phase, smart monitoring and data integration of cyber-physical systems can lead to smart buildings. Accordingly, research on DT in FM has concentrated on information integration and data-rich models [1].

4.5.1. Challenges and barriers

Rich data on the components of the facility can be found in digital models; however, past O&M data needs to be manually updated in the digital model as of right now [1]. By addressing this problem, DT may make it easier for data to be integrated and exchanged in real-time for intelligent asset management. Furthermore, because knowledge modeling can represent domain knowledge, it can help with intelligent monitoring and decision-making [1].

5. Limitations and future directions

Fig. 13 shows an overview of the future directions for the research themes studied. Numerous publications pertaining to the research theme discussed in Section 4.1, Smart Facilities Management, are anticipated to soar in number because of the building industry's fast-growing interest in BIM and digital technologies. Consequently, it is possible that some issues have not been thoroughly investigated yet, which would broaden the categories created by Ghansah's [60] research. To fully realize the potential of 5G in smart building and facility management—that is, to facilitate seamless connectivity and improve operational efficiency—it is imperative to address the ongoing commercialization of new wireless networks, 5G hardware products, limited trans-border deployments, and the necessity of ensuring cost-efficient design and implementation [55]. Other issues that need to be addressed include maintaining data security, ensuring interoperability across heterogeneous devices, and striking a balance between energy usage and sustainability. Further study addressing these issues can have a major positive impact on DT integration in SFM.

Addressing the challenges related to the research theme in Section 4.2, Geographical Information Integration, research should focus on the development of a unified semantic data model that integrates all aspects of urban systems—from buildings to transportation networks— to enable more sophisticated and autonomous smart city functions. Therefore, how to build an integrated platform containing many semantic attributes will be one of the main research hotspots in the field of GIS and BIM integration soon [29]. It is essential to establish an interoperable platform that supports the continuous update and management of smart city data, which is crucial for evolving cities into fully integrated smart built environments [66,72]. The incorporation of emerging technologies such as AI and machine learning can further improve the predictive capabilities and efficiency of urban facility management systems by collecting and analyzing large amounts of relevant data to support decision-making and provide insights such as predictive maintenance [66,70]. As a result, more research is needed on the integration of AI and ML with DTs at the city level. Addressing these challenges through additional research can significantly improve cities' management and operation as well as their resilience to risks and disasters.

To address the identified challenges in Section 4.3, future research should focus on improving the reliability of DTs by developing approaches for automated data analysis and quick modeling, as well as developing geometrically and semantically correct DTs for infrastructure maintenance and monitoring. In addition, research should focus on comprehensive risk assessment models that include a variety of risks and real-time data, such as weather forecasts and traffic data [74]. Integrating sustainability into strategic "remedial planning” and using AI for real-time data analysis can significantly improve the capabilities of smart cities [73]. Moreover, future research should address challenges such as incorporating multisensory data, ensuring data quality, and implementing theoretical knowledge in real-world scenarios [75]. Sakr & Sadhu also propose that future research use "compatible open-access software technology” to encourage greater adoption of DT applications. Future research can focus on improving IoT systems by developing multimodal sensors capable of capturing a variety of parameters. Furthermore, there is a call to create a comprehensive bank of case

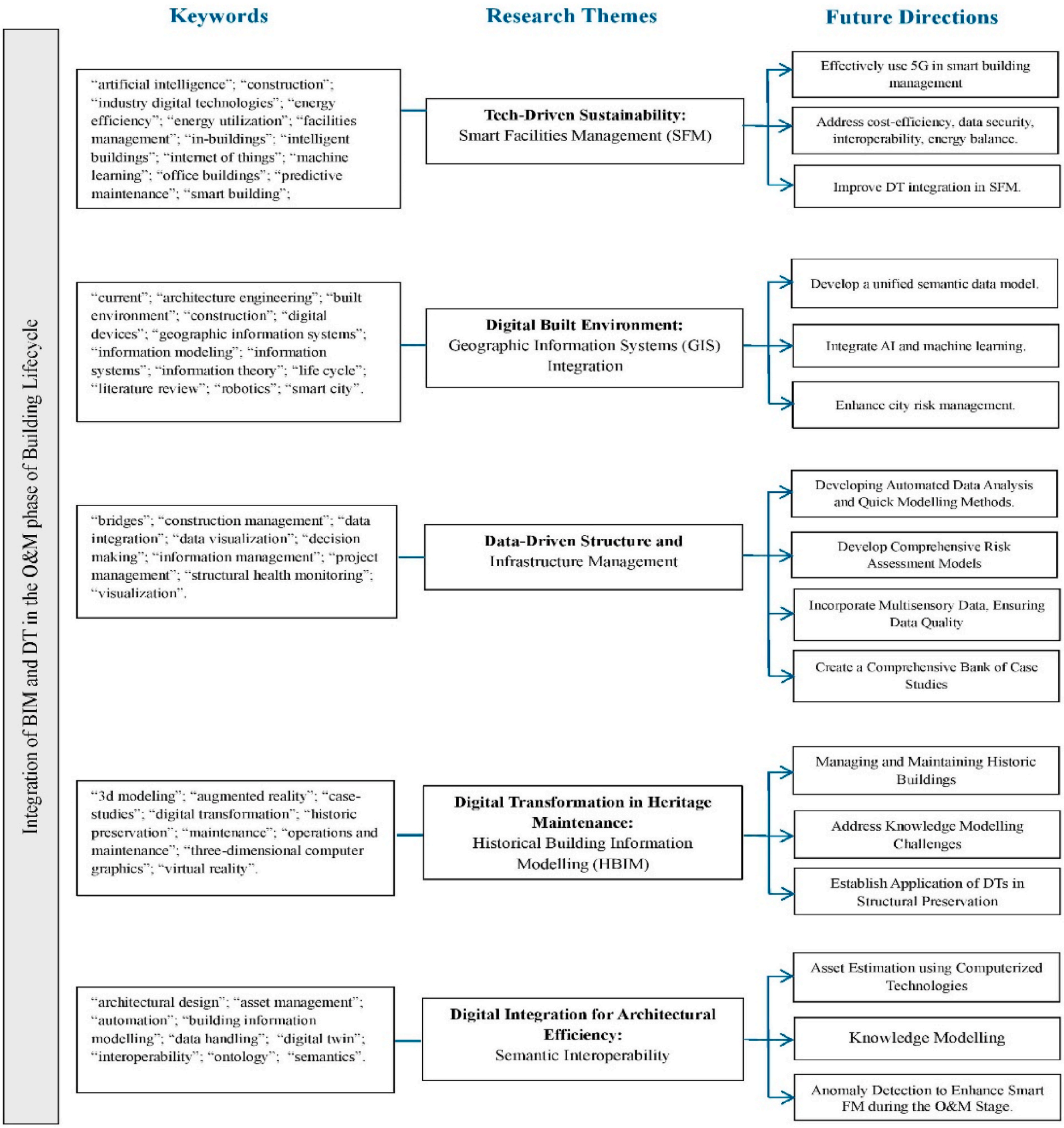

Fig. 13. Roadmap of future directions based on the studied key themes.

studies involving DT for infrastructure management, based on trials, failures, and successes, to help create a common consensus on the standards and protocols that a DT should follow [76]. Such efforts would support a data-driven approach to infrastructure management for a successful DT and BIM implementation in the O&M phase of infrastructure [75,76].

Tackling the challenges in Section 4.4, it is critically necessary to apply HBIM to integrate semantic data and use it for heritage building management to support organizations and owners in making important decisions throughout the building's lifespan. Thus, by including semantic data from many stakeholders, the HBIM's current capabilities can be expanded to support future documentation, restoration planning, and FM initiatives. The use of BIM in restoration planning and facilities management (FM) of historic buildings is still lacking in study, and the studies that have already been done do not provide the precise data required for managing and maintaining historic buildings. It is uncommon to address the execution of maintenance programs for heritage buildings, such as preventative and corrective maintenance [77]. Furthermore, more study and creative thinking are required to establish the meaningful application of DTs in the context of Built Cultural Heritage (BCH) structural preservation.

As for the challenges discussed in Section 4.5, it is still not possible to find a workable solution for the interchange, data integration, and interoperability of semantically rich data from the as-built environment that is gathered using a variety of tools (such as sensors, video cameras, and photogrammetry tools) and inspection reports to the virtual model for well-informed decision-making in FM. Future studies should investigate knowledge modeling more thoroughly [3,14]. Additionally, anomaly detection, semantically rich data interchange, and the ability to estimate an asset's remaining useable life using computerized technologies, computation modeling, and knowledge modeling are some of the most crucial components of smart FM during the O&M stage [14]. Therefore, the application of computerized maintenance management systems for DT in FM should be the main emphasis of future research in this field.

6. Conclusion

The operation and maintenance (O&M) phase, the longest and costliest in the building lifecycle, has received limited attention regarding the integration of Building Information Modeling (BIM) and Digital Twins (DT). Using 385 academic publications from the Scopus database and tools such as VOSviewer, this study revealed key patterns, trends, and collaboration in this growing field. It also revealed challenges, barriers, and emerging themes like "Tech-Driven Sustainability" and "Digital Transformation in Heritage Maintenance," while identifying promising areas for future exploration. This study contributes to the field by synthesizing bibliometric trends, advancing research on the O&M phase, and providing actionable insights to address research and practice gaps. The findings of this study are summarized as follows:

1. This study advances the focus on BIM and DT integration in the O&M phase, an underexplored yet critical stage of the building lifecycle. A performance analysis using Biblioshiny revealed steady growth in this research over the past 17 years, with a remarkable surge in publications since 2018. This analysis identified 385 documents, nearly 45 % of which were published in the past 16 months, demonstrating the dynamic and collaborative nature of the field.
2. A closer look at the nature of the publications reveals that conference papers dominate the field, suggesting a focus on rapidly disseminating preliminary findings within the research community. While this trend reflects the novelty and fast-paced development of the field, it underscores the need for more rigorous, peer-reviewed research to ensure the reliability, depth, and practical applicability of findings.
3. Geographical analysis reveals significant underrepresentation in regions such as the Middle East, Africa, and South America, while European and East Asian countries, particularly Italy, China, and the UK, lead in contributions and citations. Expanding research in underrepresented regions is essential to fostering globally inclusive advancements in BIM and DT integration.
4. Practical gaps such as real-time decision-making, data interoperability, and predictive analytics remain challenges for BIM and DT integration. These findings reveal the urgent need to bridge the gap between theoretical contributions and real-world applications to ensure that BIM and DT technologies achieve their potential in optimizing O&M processes.
5. The analysis identifies a lack of practical applications in existing research, as evidenced by the top-cited documents and citation analysis, outlined in Table 6. This highlights the need to bridge the gap between theoretical contributions and real-world implementation, ensuring that BIM and DT technologies achieve their potential in optimizing O&M processes.
6. Document co-citation analysis showed that Ref. [13] plays a central role and has significant influence in the field, with 100 co-citations. This finding underscores the importance of certain key works that have shaped the development of BIM and DT integration research.
7. By identifying emerging themes such as "Tech-Driven Sustainability," "Digital Transformation in Heritage Maintenance," "Digital Integration for Architectural Efficiency," and "Data-Driven Infrastructure," this study provides a roadmap for future studies in Facilities Management (FM) innovation. These insights emphasize the evolving priorities of the field and offer high-impact areas for future exploration.
8. This study lays a comprehensive foundation for advancing BIM and DT integration in the O&M phase. By consolidating trends, identifying challenges, and offering actionable solutions, it provides a roadmap for enhancing data-driven decision-making, energy efficiency, and stakeholder coordination. These findings will drive technological innovation and foster global advancements in smart Facilities Management practices.

CRediT authorship contribution statement

Aya Elshabshiri: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ameera Ghanim:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Aseel Hussien:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Aref Maksoud:** Writing – review & editing. **Emad Mushtaha:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

BIM - Building Information Modeling
DT - Digital Twin
O&M – Operation and Maintenance
AEC - Architecture, Engineering and Construction
FM - Facilities Management
IoT - Internet of Things
AI - Artificial Intelligence
ML - Machine Learning
GIS - Geographic Information Systems
HBIM - Historical Building Information Modeling
CIM - City Information Modeling
AR - Augmented Reality
VR - Virtual Reality
MR - Mixed Reality
CDE - Common Data Environment
TLS - Terrestrial Laser Scan
BrIM - Bridge Information Modeling
BMS - Bridge Management Systems
DSS - Decision Support System
SFM - Smart Facilities Management
BCH - Built Cultural Heritage
SHM - Structural Health Monitoring

Data availability

No data was used for the research described in the article.

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