Review Article

A Review of the Digital Twin Technology in the AEC-FM Industry

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The Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry is increasingly affected by digital technologies that monitor sensor network data and control automation systems. Advances in digital technologies like Digital Twin offer a high-level representation of buildings and their assets by integrating the physical and digital world. This paper examines patterns, gaps, and trends in the AEC-FM sector and contributes to digitalization and automation solutions for building management. This work covers a broad range of research topics, from intelligent information management of complex models to building information management and the interaction of building systems, where researchers are increasingly interested in using the Digital Twin to manage their information and in developing new research lines focused on data interchange and the interoperability of building information modeling (BIM) and facility management (FM). After a complete bibliometric search of several databases and following selection criteria, 77 academic publications about the Digital Twin application in the AEC-FM industry were labeled and clustered accordingly. This study analyzed in detail the concept of key technologies, including "Digital Twin in Facility Lifecycle Management," "Digital Twin-Information Integration Standards," "Digital Twin-Based Occupants Centric Building Design," "Digital Twin-Based Predictive Maintenance," "Semantic Digital Twin for Facility Maintenance," and "Digital Twin-Based Human Knowledge." The findings show that information standardization is the first major hurdle that must be overcome before the actual use of Digital Twin can be realized in the AEC-FM industry. Based on that, this paper provides a conceptual framework of Digital Twin for building management as a starting point for future research.

1. Introduction

The AEC-FM industry may enter the fourth industrial revolution with the aid of Digital Twin technology. This technology is considered revolutionary because of its various purposes, including simulating, helping to make decisions, and the possibility of autonomy. Therefore, the AEC-FM industry faces an unavoidable transformation to the fourth industrial revolution [1, 2]. Digital Twin aims to improve asset design, project execution, and asset operation by incorporating information and data throughout an asset's lifespan [3, 4].

Digital Twin has become a trend in many sectors. The term has been expanded to include various uses, from basic digital models that focus on visualization to sophisticated cyber-physical systems. For the AEC-FM industry, Digital Twin is a broad concept with many implications. Very often, the concepts of BIM and Digital Twin are confused. The fundamental purpose of BIM is to create a 3D-model extension of a real-world item, while the significant function of a Digital Twin is to emulate the thing it reflects. By incorporating data and information throughout the lifespan of an asset, it is possible to exchange it with other Digital Twin simulators and programs. These interactions allow the Digital Twin to be a vital decision-making source during the asset's lifetime.

1.1. Definition of Digital Twin. Having a digital model for an asset is not enough to provide whole-life cycle asset management, especially in the maintenance and operation phase.

Therefore, there is ongoing research on how to incorporate the Digital Twin concept that integrates Artificial Intelligence, Machine Learning, and Big Data Analytics to create dynamic models that can learn and update the status of the physical counterpart from multiple heterogeneous data sources [5].

What can Digital Twin offer to the building sector? To answer this question, it is necessary to first look into what a Digital Twin is. As several industries are using this concept (e.g., space and air force, marine, offshore, and aerospace industry), there are multiple definitions of the term. However, the CIRP Encyclopedia of Production Engineering [6] released a definition of the term Digital Twin in 2019 that seems to cover most use cases: *"A digital twin is a digital representation of a unique active product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviors through models, information, and data within a single or even across multiple life cycle phases."*

The definition uses the phrase "unique product." The reason for this is to emphasize the need for a Digital Twin to represent only one asset because of the accumulation of information. The product's history is essential as previous damage or repairs will significantly affect how the product will respond to loads in the future. Another aspect that is worth looking into in the definition is the following phrase: "[\enleadertwodots] or even across multiple life cycle phases." It is to underline the possibility of letting the Digital Twin follow the product even after the end of its life cycle in the event of refurbishing or reusing some of the components in other projects, and the history of the components will be valuable.

1.2. The Origin of Digital Twin. Using models to represent the real world is not new within the engineering field. NASA built physical "twins" of the spacecraft in the Apollo program in 1967-1972 [7]. However, it is only in the last quarter of the 20th century that it has been possible to create virtual replicas within computers' digital space. The origin of the Digital Twin concept is by many [8–10] credited to Michael Grieves, who in 2002 held a presentation about product life cycle management. In the presentation, Grieves showed all of the essential parts of a Digital Twin model: the real object, the virtual object, and the gathering and processing of data between the physical asset and the digital replica. Grieves initially referred to it as a "conceptual ideal for product life cycle management." Later on, Grieves changed it to "Mirrored Spaces Model" and then called it "Information Mirroring Model." [6] Finally, Grieves wrote an article in 2011 with John Vickers, who worked for NASA, and in this article, the term "Digital Twin" was used [6]. The main parts of Digital Twin can be seen in Figure 1, where the simulation model must be validated by the measurements from the physical object using technology, such as laser scanners, drones, sensor data, etc. Once the model is validated, it can give insight into how the physical object acts under various simulated situations, making better decisions and streamlining operations and predictions.

Michael Grieves recently published research about the common misunderstanding that the Digital Twin does not exist unless there is a physical object [11]. According to Grieves, the primary criterion for determining if a digital model is a Digital Twin is whether the model is designed to become a physical product with a physical counterpart. Grieves gives an excellent example here. A flying carpet Digital Twin will never become a Digital Twin because we cannot make it a physical object.

1.3. Scope and Structure of the Paper. The AEC-FM industry is in the midst of the fourth industrial revolution, a period of unavoidable digital transformation [1]. Digital Twins can usher in the fourth industrial revolution in the AEC-FM industry. The aerospace sector began using the Digital Twin roughly a decade ago to develop new planes and vehicles. However, the Digital Twin idea is mainly used in designed goods, manufacturing equipment, and production lines to manage product lifecycles and meet Industry 4.0 criteria. It is viewed as an innovative method of integrating and controlling an asset throughout its lifespan because of its numerous applications, including simulation, decision support, and the possibility for autonomy. However, to compete in the AEC-FM industry, businesses must find new and inventive ways to revolutionize their work [12]. The subject matter is critical in allowing the digital and physical elements to be appropriately integrated. Digital Twin may help offer more successful asset design, project execution, and asset operation by integrating data and information throughout the lifespan of an asset [13, 14].

Information-based systems, such as BIM, which seamlessly integrate information, will allow advances in AEC-FM operations and increase the project's efficiency and effectiveness throughout the project's lifetime. However, BIM will not satisfy the need for an automation solution in the AEC-FM industry alone, nor will it deal with the intelligent data revolution and interoperability issues. BIM must be combined with emerging technologies that are only partly applied in the AEC-FM industry, where there is minimal research to close this gap to enhance building management and design.

The Digital Twin activities may enhance AEC-FM operations by improving data management and processing using large-scale data, information, knowledge integration, and synchronization. It does this by dynamically integrating data and information throughout an asset's lifespan. Combining a virtual information model with real-time data might significantly improve decision-making over the whole building's lifespan. The integration of real-time data via IoT sensors and devices on the physical system enhances adaptive updating to serve the information for further machine learning and artificial intelligence integration to coordinate and automate the physical counterpart of the digital model, following operational changes.

This paper's novelty lies in investigating three databases, namely the Web of Science, Scopus, and Google scholar, about the Digital Twin in the AEC-FM industry facing the manufacturing and automotive industry. Compared to other

Physical Object

Internet of things		
Laser scanner	3D printing	Drones
Sensors	Big data analysis	---

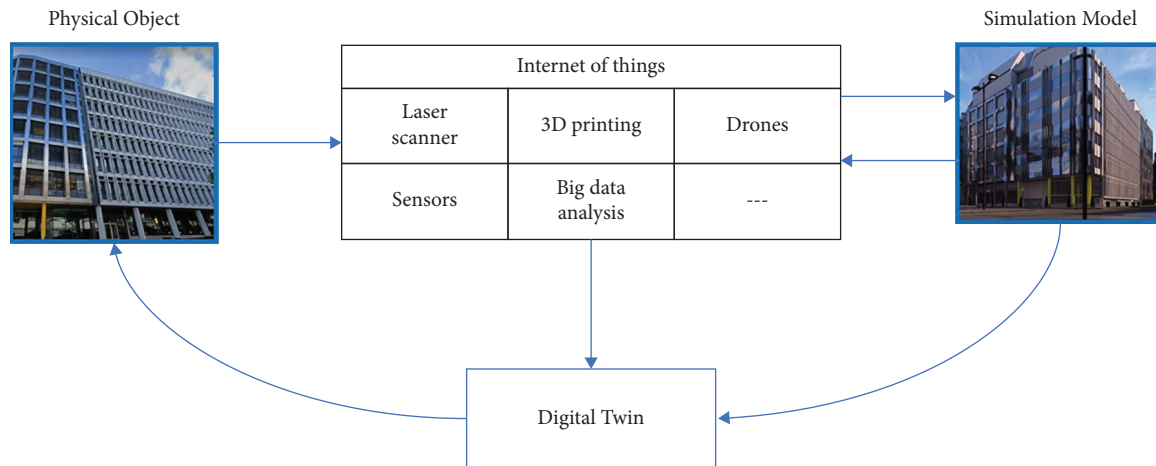Simulation Model

Digital Twin

FIGURE 1: Digital Twin technology

review papers [13, 15, 16], this study is one of the few studies that focus on Digital Twin technology within the AEC-FM industry.

In addition, there are similar works to our paper that have been published recently. Deng et al. [17] performed an extensive assessment to identify the developing technologies aiding the transition from BIM to Digital Twins in built environment applications. The emphasis was on BIM rather than supporting technologies like Digital Twin information transmission systems. Our work focuses more on the ideal digital twin model for AEC-FM. Fjeld [18] examines the state of Digital Twin knowledge in the Norwegian AEC-FM industry to establish a standard definition of "Digital Twin" technology. However, only Scopus was used as a database in her study. Caramia et al. [19] conducted a systematic literature study to examine the Digital Twin in AEC/FM. They chose a limited period for their study (2018 to 2020). Moreover, there are various gaps in the use of Digital Twin, such as occupant comfort, predictive maintenance, etc., that are not addressed in their research.

The awareness of the Digital Twin in the AEC-FM industry will improve as more people get familiar with the idea, the technology, and the current state of the art. A conceptual framework for an ideal Digital Twin AEC-FM industry is also proposed in this study, which will serve as a guideline for future research.

The following sections of the study investigate the current status of Digital Twin research in the AEC-FM industry to identify patterns, trends, and gaps in this area.

2. Methodology

This study examines whether technologies and applications in the AEC-FM sector are ideal for Digital Twin technology. There is currently no comprehensive inquiry focusing on understanding how specific cutting-edge technologies complement Digital Twin to reach their full potential or whether there is any chance of combining more than one technology to assist Digital Twin.

This article's technique is divided into three steps, as shown in Figure 2. Data collection (stage 1) involves retrieving an initial number of articles, deleting extraneous publications, and selecting just particular publications and relevant categories. Stage 2 includes a scientometric analysis, followed by the findings (stage 3). The following are further details about these stages:

2.1. Data Collection. Literature exploration was performed on the Scopus, Web of Science, and Google scholar databases to ensure more comprehensive and robust findings rather than just gathering data from a single one. The OR and AND search benchmark was used to do the keyword-based search, for example, LIMIT-TO (EXACT KEYWORD, "Digital Twin") OR LIMIT-TO (EXACT KEYWORD, "Life Cycle") OR LIMIT-TO (EXACT KEYWORD, "Architectural Design") OR LIMIT-TO (EXACT KEYWORD, "Construction Industry") OR LIMIT-TO (EXACT KEYWORD, "Information Management"), etc. The study examines publications published between 2016 and 2022 (ending on 12th February). The reason for choosing this time interval is because there were no pieces of research about Digital Twin in AEC-FM before 2016. The result of the first stage was 158 research publications. A refinement of the search followed this to exclude many irrelevant papers that may have no bearing on this study. The papers selected were based on published articles, conferences, and reviews, as these publications can give a thorough overview of extant research [20]. For instance, only English-language articles were collected since VOSviewer was used to evaluate scientometric data, which only supported English-language papers. VOSviewer software was employed to do bibliometric data analysis on the databases' information (Figure 2). VOSviewer is a visualization application that uses natural language processing methods and text mining techniques to help analyze massive networks. It is frequently used in scientific research [21, 22]. The VOSviewer application may be used to do scientometric analyses, which may entail studying citation links between articles or journals, cooperation ties between researchers, and co-occurrence interactions between scientific terms. However, VOSviewer has a limitation in consolidating data duplication. As a result, we manually eliminate duplicate studies to avoid any noise in the data. After that, new groups
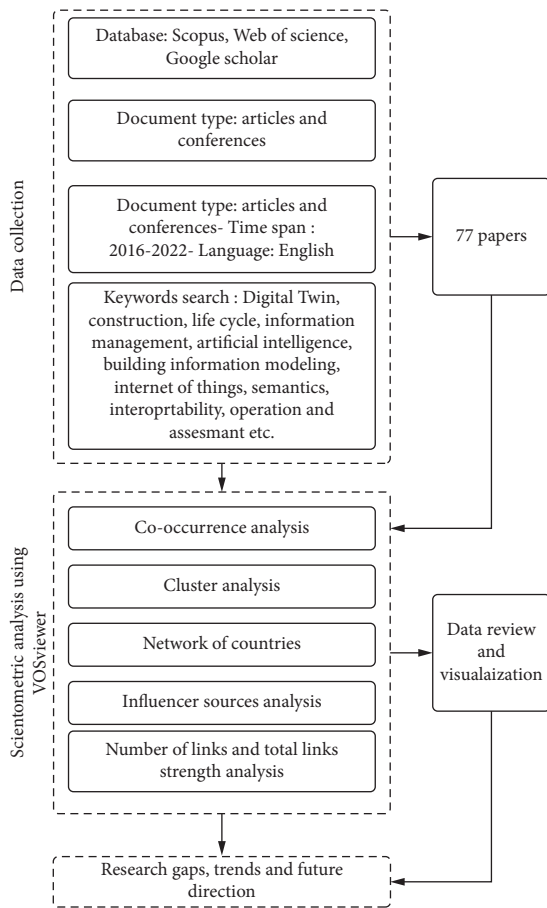
FIGURE 2: Investigation workflow of AEC-FM digital twin research.

were selected for this article based on other refining criteria, including subject area (engineering, environment, etc.) and source type (journal and conference proceedings). The final literature volume was 77 papers.

2.2. Scientometric Analysis. Analyzing articles by hand is becoming increasingly difficult because of the rapid growth of research. As a result, this study used the VOSviewer® as an analytical tool and classified and evaluated the literature using a conventional quantitative and qualitative manner. The program supports Distance-based maps, and the user can select the sort of analysis to do. This software's capabilities include the analysis of coauthorship, co-occurrence, citations, bibliographic coupling, and cocitations. There is a wide range of uses for each of these. Aside from that, this study is primarily concerned with determining the link between current technology and the Digital Twin. Consequently, this paper's goal necessitates that the primary focus is co-occurrence analysis and link analysis. Citation analysis is one sort of analysis that can be used in the future. Firstly, co-occurrence analysis is used to examine the co-occurrence of terms in at least two separate publications [23]. The relationships between keywords are determined by the frequency with which they are used in documents [24]. The study themes were determined using cluster analysis (Section 3.1). Secondly, the number of links reveals how many

times a term is linked to other keywords. The overall link strength metric measures the strength of a keyword's linkages to other keywords. Additionally, the average publication year of the papers that contain a term provides context for the keyword's presence in the associated literature. The more recent the average year of publication, the more current the keyword and subject of the study.

Moreover, influencer source evaluations were conducted to include all critical publications from the most prestigious journals, such as automation in construction, applied science, etc.

2.3. Research Gaps, Trends, and Future Direction. To provide a thorough insight into the Digital Twin technology in AEC-FM and the future research in this domain, this stage includes a discussion of the application fields of Digital Twin.

3. Results

3.1. Science-Based Keyword Mapping and Analysis. The main features in the study are identifiable by keyword search [25]. The knowledge of words and phrases was gained using text mining and natural language processing techniques used in VOSviewer [24]. For authors who fail to include relevant keywords, a few databases employ subject headers to help prevent overlooking relevant terms. In this study, keywords generated by the authors and indexes were utilized for scientific analysis. A keyword filter was used to count the number of phrases used in the study. The extent of a document is shown by the number of times a term appears.

The network of terms co-occurrence is made visible in Figures 3–5 using bibliometric data analysis. The technique used to develop the graphic is based on a minimum of four keywords that are close to one another.

The circles and labels in Figures 3–5 indicate the keywords in the respective figures. The weight of a term is represented by the circle's size and the label's size. The distance between two keywords in a network is used to determine how closely they are linked to one another. Because of their significant correlation, two keywords are placed closer together in the network, whereas their lesser correlation brings them farther apart. Moreover, colors represent the groups of related keywords (clustering).

As seen in Figures 3–5, the analysis of keywords from findings indicates that four main terms form together with the Digital Twin concept in the AEC-FM industry: BIM, IoT, ML, and Building Management System (BMS).

The keywords employed in this study were both author-generated and index keywords, which were combined to complete the analysis. A total of 52 keywords out of 1244 passed the criteria of 6 co-occurrences. Following the consolidation of the keyword list, 41 keywords were selected, which are presented in Table 1.

The study patterns, gaps, and trends in Digital Twin research were explored further in light of the research findings on the field's evolution. The following sections of the article discuss research trends and highlight research gaps in the field of Digital Twins.
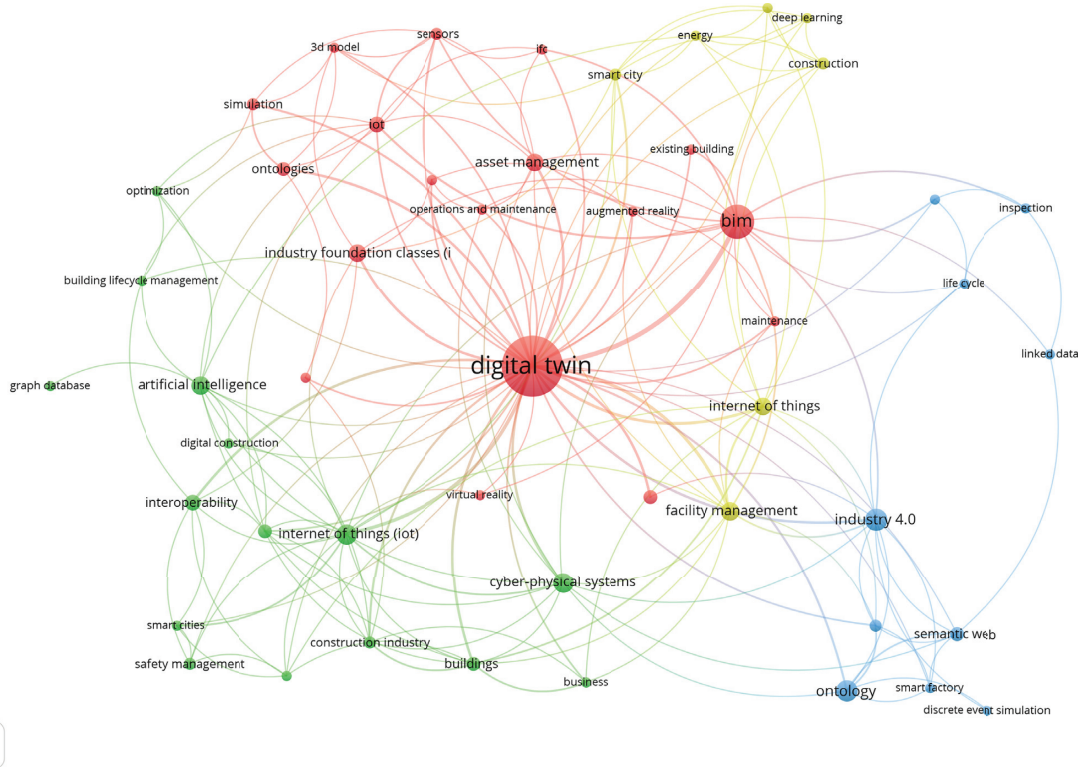
FIGURE 3: Network representation of keyword co-occurrence extracted from the Web of Science of Digital Twin research in the AEC-FM industry from 2016 to 2022.

3.2. Total Link Strength and Average Year Published. The most important keywords in the Digital Twin study undertaken in the AEC-FM industry have high overall link strength and a high occurrence frequency. Table 1 shows the findings of the scientometric study, which revealed that the keyword Digital Twin had the highest overall link strength (123). The lifecycle (38), architectural design (37), and information management (25), respectively, came next. Decision making, constructing information models, project management, and artificial intelligence were the terms with the subsequent most significant overall link strengths. However, there is a significant gap in Digital Twin research in the areas of predictive maintenance (10), interoperability (8), information systems (7), energy utilization (7), ontology (6), asset management (5), safety engineering (5), life cycle management (5), semantics (5), data fusion (5), and linked data (3).

For years, the AEC-FM industry's attention has focused on Digital Twin research as a product lifecycle management technique, and these two terms have become the most important in research. In the building construction industry, Digital Twins are now used across the whole project lifetime, which explains why this term is so important. Every building project generates complex data. Using modern Digital Twin research in the AEC-FM industry, we can put this massive amount of data to good use in facility management. As a consequence of the AEC-FM industry's digital transition, a cognitive-capable Digital Twin of the building as a physical asset was created. Digital Twin study promises to enhance building information models, data processing, and efficiency in information administration. One of the most challenging tasks in the project lifecycle is gathering and analyzing data. Thus, information management is critical in Digital Twin research.

In addition, energy utilization, built environment, facility management, building information model, and artificial intelligence are relatively new keywords that have become increasingly popular in association with Digital Twin research in recent years, as shown in the right-most column of Table 1. The chronological sequence of the keywords implies that researchers are more likely to investigate information use using BIM-based procedures than through traditional methods.

3.3. The Reviewed Sample Size. As shown in Figure 6, the quantity of papers produced between 2016 and 2022 is presented annually. During this period, the quantity of articles linked to Digital Twin in AEC-FM has increased. The trend is even more evident in 2019 with the growing quantity of research publications. The total number of papers published in the past seven years was approximately 77 when this paper was prepared. Thus, the exponential increase of Digital Twin research in AEC-FM demonstrates the dramatic influence on the AEC-FM community.

Several engineering and computer science journals have published articles on Digital Twin research outputs, according to the distribution of Digital Twin research outputs in the Table 2. Among the primary reasons for this

FIGURE 4: Network representation of keyword co-occurrence extracted from Scopus of the Digital Twin research in the AEC-FM industry from 2016 to 2022.

development is that digitalization and automation are primarily achieved via the use of tools and techniques created in those fields [9].

3.4. Active Nations in the AEC-FM Industry Digital Twin Application Research. To discover which nations are most involved in the AEC-FM industry digital twin research, the study employed the "coauthorship" analysis, "country" unit of analysis, and "fractional counting" as the counting technique. Fractional counting was used to limit the influence of highly cited articles in the bibliographic coupling network and to minimize the impact of publications with numerous authors. A minimum of one document and one reference per nation was used to establish the optimal network. In the investigation, 13 nations met the criteria and were thus included in the resulting network. In Figure 7, the network indicates that the United Kingdom, United States,

Italy, and Australia were the major contributors to Digital Twin research in the AEC-FM industry.

There is a limitation of international cooperation in the AEC-FM sector in Digital Twin research. Many of the papers have been published recently because of the relative infancy of the Digital Twin and the delayed acceptance of new technologies in the AEC-FM sector. Because of this, it is necessary to foster stronger cooperation across nations to facilitate global knowledge exchange and transmission.

3.5. Scientific-Based Analysis of Sources. Scientific-based analyses were utilized to find sources on the topic of Digital Twin that was published in the AEC-FM sector. The threshold for the minimum number of documents was one. A total of 20 sources matched the criterion. Furthermore, for each of the 20 sources, the overall strength of the citation connections with other sources was determined.
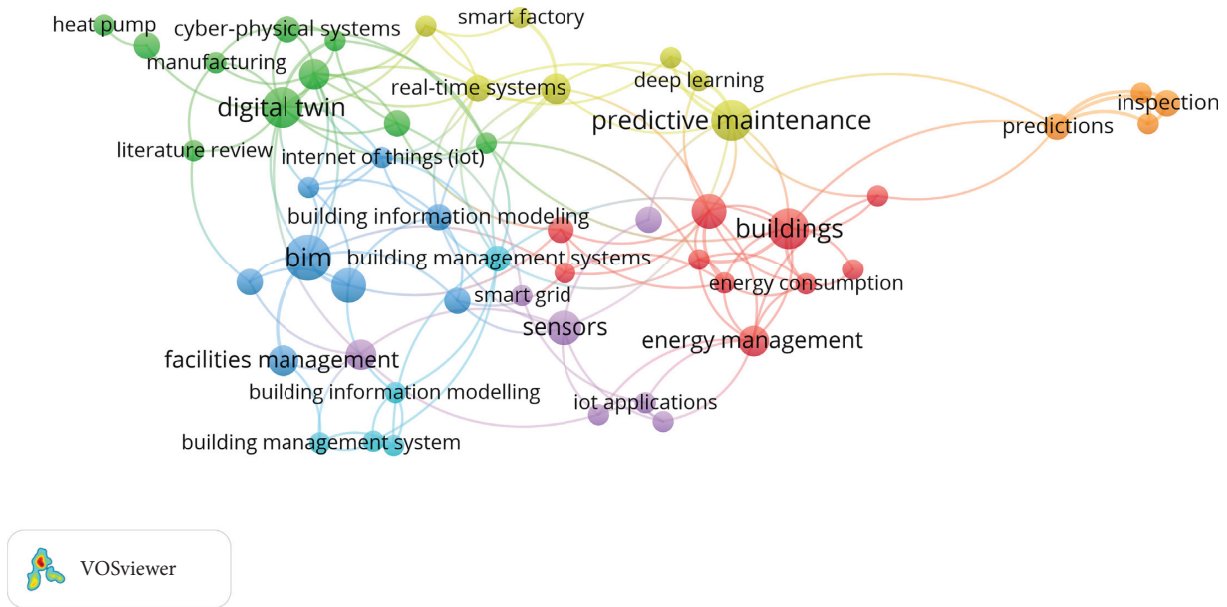
FIGURE 5: Network representation of keyword co-occurrence extracted from Google Scholar of the Digital Twin research in the AEC-FM industry from 2016 to 2022.

TABLE 1: A scientometric study of items related to Digital Twin research in the AEC-FM industry from 2016 to 2022.

Keywords	Cluster	Number of Links	Total link strength	Average published year
Big data		27	9	2019.67
Facility management		21	8	2020.75
Information management	Digital twin in facility life cycle management	42	25	2020.16
Life cycle		45	38	2020.18
Life cycle management		18	5	2019.60
Project management		33	20	2019.90
Data fusion		11	5	2020.40
Information modeling		24	11	2020.55
Information theory	Digital twin-information integration standards	35	17	2020.24
Interoperability		20	7	2020.00
Optimization		14	10	2020.80
Data acquisition		24	9	2020.22
Data handling		17	10	2020.10
Digital storage		24	8	2020.38
Digital twin	Digital twin-based occupants centric building design	51	123	2020.32
Energy utilization		14	7	2020.86
Intelligent buildings		21	7	2020.29
Energy management		15	9	2020.12
Construction process		19	7	2020.14
Embedded systems		33	16	2020.19
Human-robot collaboration		9	5	2020.00
Information systems		19	7	2020.14
Information use	Semantic digital twin for facility maintenance	13	5	2020.40
Real-time monitoring		14	7	2020.14
Semantics		15	5	2020.20
Ontology		16	6	2020.12
Linked data		18	3	2020.30

TABLE 1: Continued.

| Keywords	Cluster	Number of Links	Total link strength	Average published year
Artificial intelligence		27	19	2020.32
Asset management		16	5	2019.60
Data analytics		18	5	2020.00
Decision making		41	23	2020.26
Digital technologies	Digital twin-based predictive maintenance	19	13	2020.23
Maintenance		24	10	2020.30
Metadata		15	5	2018.80
Risk management		13	5	2018.60
Predictive maintenance		22	8	2018.72
Architectural design		46	37	2020.32
Building information modeling		36	20	2020.25
Built environment	Digital twin-based human knowledge	15	6	2020.83
Digital twins		28	12	2020.92
Internet of things		30	11	2020.27
Safety management		15	5	2020.60
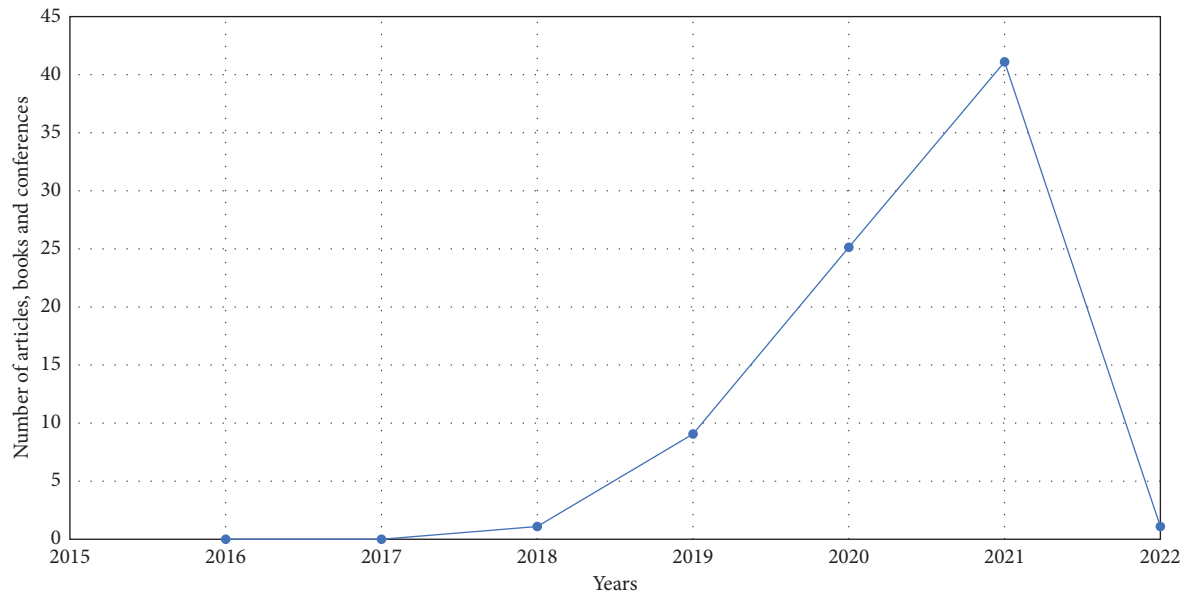
FIGURE 6: The number of articles published each year in the AEC-FM industry regarding Digital Twin research from 2016 to 2022.

Four major quantitative factors are listed in Table 2. Several articles highlight the importance of the sources' contribution to the field of study. Links indicate the relationship between the specified source to other sources. Total link strength reflects how strong a journal's link with other journals is. Finally, the total number of citations is tallied for each reference across all years.

A network diagram illustrates the outcome of journal citation analysis (Figure 8). Automation in Construction, Applied Sciences, Engineering Construction, and Architectural Management, Journal of Information Technology in Construction, Construction Innovation, and IEEE Access publishes the most significant number of papers in Digital Twin in AEC-FM. In contrast, Automation in Construction, Applied Sciences, Engineering Construction, Architectural Management, Construction Innovation and the Proceeding

of the 34th Annual Arcom 2018 are the top sources with the highest citation. Therefore, according to these comparisons, Automation in Construction, Applied Sciences, Engineering Construction, and Architectural Management is the most influential source in Digital Twin in AEC-FM.

4. Discussion

The evolution of Digital Twin research throughout time, research patterns, gaps, and trends were evaluated and addressed in this part based on study findings. The sections that follow highlight research trends and define research needs in the field of Digital Twin research. Of these results, the most notable impact of Digital Twin research is found under the topic, "Digital Twin in Facility Lifecycle Management." At the same time, there is a wide gap in research

TABLE 2: The AEC-FM industry's sources' quantitative measures concerning the digital research.

| Source title	Number of articles	Links	Total links strength	Citation
Automation in construction	11	9	14	169
Applied sciences Switzerland	4	3	5	17
Engineering construction and architectural management	4	5	6	22
Journal of information technology in construction	4	5	7	4
Construction innovation	3	1	1	24
IEEE access	3	1	1	3
Sensors	2	1	1	3
Smart and sustainable built environment	2	4	4	11
Buildings	2	2	3	3
Electronics Switzerland	2	2	2	3
IEEE engineering management review	2	1	1	8
IFAC papersonline	2	1	1	1
International journal of safety and security engineering	2	1	1	6
Journal of asian architecture and building engineering	2	1	1	2
Journal of computing in civil engineering	2	2	2	0
Journal of building engineering	1	2	3	0
Proceeding of the 34th annual arcom 2018	1	1	1	15
Sensors Switzerland	1	1	1	3
Tunnelling and underground space technology	1	1	1	0
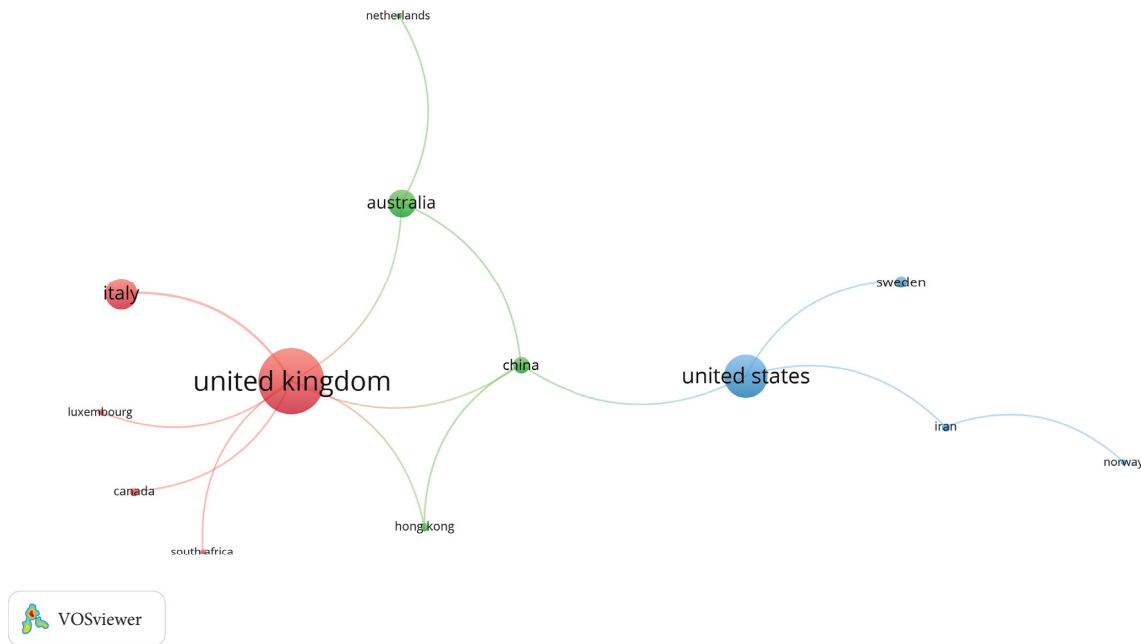
FIGURE 7: Countries making important contributions to the Digital Twin research in the AEC-FM industry.

that looks into "Digital Twin-Information Integration Standards," "Digital Twin-Based Occupants-Centric Building Design," "Digital Twin-Based Predictive Maintenance," "Semantic Digital Twin for Facility Maintenance," and "Digital Twin-Based Human Knowledge" (Figure 9).

4.1. Digital Twin in Facility Lifecycle Management.

Facility management (FM) accounts for almost two-thirds of the overall cost of a building's entire life cycle [26]. FM is a multidisciplinary approach to ensuring the built environment's efficiency by incorporating individuals, locations, procedures, and technologies. Maintenance management, energy management, space management, asset management, building performance, control management, sustainability management, emergency management, and other building management tasks are all included in FM. However, FM managers always struggle to access details using 2D drawings and conventional facility management systems [27, 28].

4.1.1. Asset Management and Monitoring.

Asset management refers to a group of management processes and structures covering all aspects of asset management during
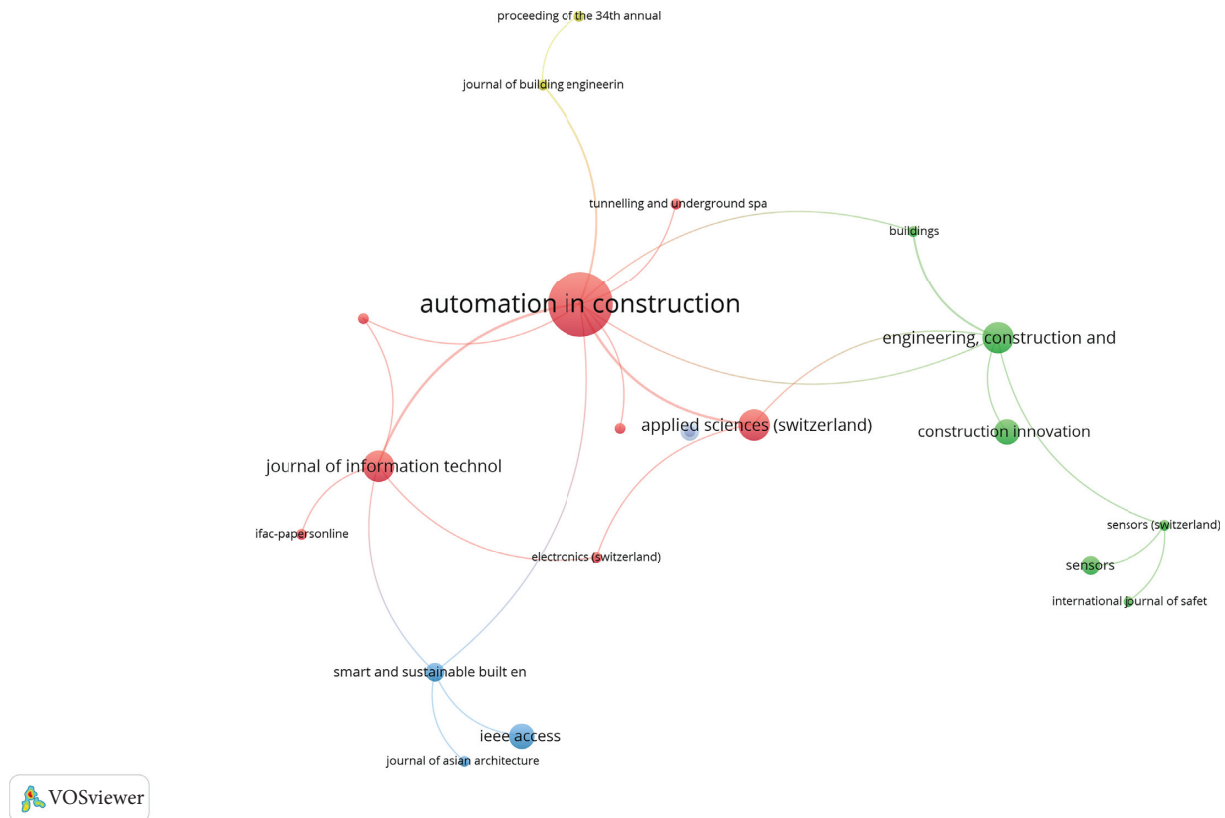
FIGURE 8: Digital Twin for AEC-FM activities uses scientific-based mapping of influencer sources.

its life cycle. It involves the management of the physical asset and the associated digital knowledge within the scope of the project [5, 29]. Likewise, BIM considers the entire life cycle of an asset, including quality control and asset management [30–34]. BIM has potential applicability and benefits in the service and maintenance stage, according to many types of research [35–37], and some leading FM organizations are pushing the use of BIM in this stage. Lee & Lin [38] explored how the BIM approach is used to construct 3D information models for building management and maintenance. However, while using BIM alone, there is no automatic condition monitoring to allow facility managers to make quick maintenance decisions. In addition, a lack of knowledge in using BIM alone will make it difficult to define asset management criteria during the design process [5]. It brings us to the power of Digital Twin technology to improve facility management maintenance and operational performance. The use of a Digital Twin would speed up the advantages and growth of BIM and other digital innovations in the asset management industry [39]. However, a well-defined and well-organized Digital Twin model is also needed to oversee current implementations, identify gaps, and include roadmaps for future progress.

4.1.2. Maintenance of Mechanical, Electrical, and Plumbing Components.

The maintenance of a building could benefit from Digital Twin by platforms assisting with checking maintainability and real-time data access. The related studies

of operation and maintenance were summarized as three main categories, including identification of physical components linked with BIM by RFID (radio-frequency identification) tags, linking physical with digital objects by connecting BIM and building management system (BMS), in addition to the visualization of problems by augmented reality or mobile BIM tools [40]. Augmented reality can be described as a real-time view of a physical world with included digital information, which enhances the user's perception of the real world [41].

The maintenance of mechanical, electrical, and plumbing (MEP) is often reactive or preventive, however, failure or future conditions cannot be prevented. Cheng et al. [27] conducted a study based on IoT and BIM to improve the maintenance strategy for building facilities. The study collected data from IoT sensors monitoring the building facilities and environment in the operation period. The future conditions of MEP components were predicted by ML algorithm, and an illustrative example stated that this method could efficiently predict the condition of MEP components.

4.2. Digital Twin-Information Integration Standards.

With the rise of new technologies, information diversity and overload can happen, all of which can lead to system fragmentation throughout the building project, difficulties for workers to consume the information timely and effectively, and burden the workers with too much or irrelevant information [42]. Integrating the buildings' information

FIGURE 9: The AEC-FM industry's "Digital Twin" item co-occurrence network visualization map from 2016 to 2022 (up to February 2022).

with the live data is not easily accessible for potential users. The problem is attributable to the difficulty in accessing the building information and the challenge to integrate this information with the live data from heterogeneous sources [43]. Bischof et al. [44] present the challenges arising from the nature of different data sources and emphasize providing semantic interoperability and data integration.

McGlinn et al. [45] developed an ontology to integrate heterogeneous data using artificial neural network, genetic algorithm, and data mining for addressing the issue of providing intelligent control suggestions to facility managers. Their findings indicate that, while BIM and IoT are promising technologies that result in broader data sets, standardization of such policies and procedures arises to be an unexpected challenge. Some efforts have been made to solve standardization issues. However, McGlinn et al. [45] have not fully tackled the challenges mentioned above in their research. The main reason is that currently, there are many BIM software with different format types. One of the proposed solutions is a cloud-based BIM system that adopts the IFC format as the BIM file upload format with a

developed web interface using WebGl [46]. On the other hand, cloud IoT can merge Cloud Computing and IoT, partially solving most IoT issues. Cloud can provide the intermediate layer between things and applications, interoperability of very high heterogeneity of devices, and real-time data analysis [47, 48].

Hence, the initial challenge to facing the practical application of Digital Twin in the AEC-FM industry is information standardization. Poorly designed and implemented information integration makes sorting large and heterogeneous data sets into useable data challenging, and doing so is more complex than anticipated. This process is very time-consuming and will hinder the future of the Digital Twin revolution [49].

In general, IoT sensors are dynamic, and FM-BIM contains static data. The standard integration method that is used for static and dynamic data is known as linked data [50, 51]. The method stores each data source effectively separately and creates a data lake that can be accessed through the data management system. When working with this method, there are two approaches to consider: ontology

linked and directly linked. An ontology-linked approach uses a query processor to make this data accessible. In the case of a directly linked approach, standardized naming formats can be used to create a direct link between BIM data points and IoT [52]. The second approach links BAS and IoT to BIM using standardized naming formats and is much simpler. In the AEC-FM industry, the information exchange protocol COBie was developed to establish a standard naming format. This was used to facilitate the integration of computerized data into BIM. This approach requires no manual tagging. Instead, connecting BIM and BAS data stores and other data sets will define the input data structure.

4.3. Digital Twin-Based Occupants Centric Building Design. Human-building interaction is one of the least developed aspects of building science, even though most buildings are built for human occupants with the functions of delivering comfortable, healthy, accessible, and secure spaces to satisfy a variety of uses [53, 54]. However, numerous post-occupant assessments show that buildings often fail to meet occupant expectations [55]. As a result, a paradigm shift is necessary to recognize that occupants and buildings have a complex and dynamic bi-directional relationship that enables new technologies and approaches to raise awareness of the importance of healthy and comfortable environments. Therefore, research is needed for the use of existing data sources such as BIM, BAS, and IoT and how to integrate them with technologies like ML and statistical modeling to build the Digital Twin model that will aid facility managers in decision-making, obtaining knowledge on occupant behavior and indoor climate and the relation between them. The following knowledge gaps have been identified in the literature:

(i) The different domains of environmental exposure have been treated in isolation in previous studies on human comfort and behavior in buildings, especially indoor air quality and acoustic, thermal, and visual comfort [56–60]. Thus, it is necessary to build a framework that investigates the effect of all those aspects on occupant comfort.

(ii) Data-driven modeling of occupant presence and activities are required to achieve new knowledge. In particular, data mining and artificial intelligence. New techniques and tools are rapidly developing and gaining traction due to Artificial Intelligence and data mining that is capable of identifying patterns and learning from the past, have improved properties and performance, or make analytical and predictive approaches more available [61]. In this domain, deep learning has emerged as a promising strategy for occupant detection in recent years [62]. The best data processing techniques should be investigated in future research for predicting occupant presence [63] or for model-predictive control [64, 65].

(iii) Integrating BIM with ML and statistical approaches with sensor data to build a Digital Twin that makes data collection more manageable and allows for the visualization of occupant feedback and HVAC conditions results to support decision-makers. There have been very few studies in this domain, and one of the limited examples is by Alavi & Forcada [34] where the authors incorporate occupant feedback from a questionnaire survey and a probabilistic model of occupant comfort into BIM.

(iv) Although many methods of calculation can provide reliable simulation approximations of building energy performance, the key source of uncertainty still lies in the occupant actions [66, 67]. Hence, it is vital to develop an occupancy ontology that enables occupant behavior and activities to be represented within construction spaces. In addition, streaming real-time data through ontology to draw patterns of occupants is missing in the reviewed literature.

4.4. Semantic Digital Twin for Facility Maintenance. To conduct analysis, predict the probability of failure, and prevent failure through systemic maintenance, facility maintenance requires various data, including location, historical maintenance records, and temperature and pressure data of facility components such as HVAC systems. Even though facility maintenance operators automated application systems, these systems still appear to them as black boxes. Furthermore, Microsoft Excel spreadsheets are still commonly used, resulting in a late response to service requests and inefficient maintenance management. However, since facility maintenance approaches are highly varied in their requirements, no single system fits all applications. As a result, researchers are increasingly focused on improving the effectiveness of information management in facility maintenance.

BIM, FM databases, and IoT networks are examples of technologies that can help build the Digital Twin, which helps with data collection, storage, and management. Early research on BIM-based FM [35, 37, 68, 69] demonstrated how BIM could be used to improve FM operations. However, the integration is difficult because each of the systems uses different data formats [70]. The lack of an information integration technique between BIM and FM is well known in the literature [71, 72]. On the other hand, developing an IoT data representation standard and a methodology for incorporating this standard with the BIM and FM systems is necessary. As a result, a strategy for simplifying and optimizing the querying process between BIM, FM, and IoT is essential. In this integration, ontology can be a solution to the complexity of Industry Foundation Classes (IFC) from BIM, lack of extracted information using Construction Operations Building Information Exchange (COBie) from FM, and different IoT formats [73, 74]. The ontology is a tool for converting domain knowledge into information that a computer can understand [75]. Hence, more research is required for the following:

(i) Development of ontologies for IoT, BIM, and FM information.

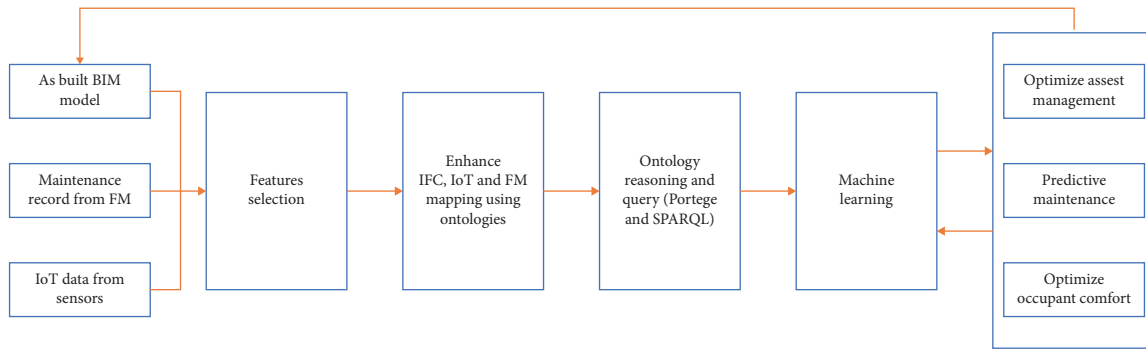(ii) Building a relationship between the three presented ontologies.

FIGURE 10: A preliminary architecture for information integration based on ontology.

(iii) Reasoning-based querying to make information more accessible for FM.

Combining ontologies, relationships, and retrieval queries create a semantic Digital Twin represented by a knowledge graph that aids in information integration and bi-directional information transfer between BIM, IoT, and FM. This paper proposes a methodology framework for data integration and facility maintenance in Figure 10. In Figure 10, the data from BIM, FM, and IoT will be exported first. Then, the most crucial feature from this data will be selected using a statistical method such as Analysis of Variance (ANOVA). After that, to map the remaining data in one system, we need to use the ontology concept. ML classification can then be applied over those ontologies to achieve several goals like predictive maintenance.

4.5. Digital Twin-Based Predictive Maintenance. Effective maintenance techniques can minimize building maintenance costs and increase building components' service life. In building maintenance management, reactive and proactive maintenance are currently implemented [76, 77]. However, reactive maintenance cannot avoid failure. Furthermore, proactive maintenance cannot forecast the future conditions and repair components to prolong their life in advance [78]. A number of studies reviewed predictive maintenance aspects [79–82]. In addition, several algorithms have been used for data processing to predict the condition of building components [83–86]. Although most of the findings investigated predictive maintenance, they provided facility managers with no accurate and practicable method to predict a building's future condition. Hence, a comprehensive method of implementing BIM and IoT with data processing to build a Digital Twin for predictive building maintenance is required. In Figure 11, we propose a Digital Twin framework of a chiller for predictive maintenance and fault detection. The data will be streaming to the building management system and then built an API in this figure. By extracting the data using the API, a digital twin model can be built in Simulink in MATLAB and then validate the MATLAB model's outcomes by using machine learning techniques. After validation, we can use the model to do several parametric studies. For example, suppose we want to predict the remaining useful life of the chiller for optimizing

maintenance schedules. In that case, we use the MATLAB model to update the model in the building management system constantly. Similarly, we can inject different faults and simulate the chiller behavior under different fault conditions using the MATLAB model.

4.6. Digital Twin-Based Human Knowledge. The predictive capabilities of Digital Twin are very promising in the building sector. Nevertheless, these features are still unable to react to unexpected events [87]. To handle this issue, the human knowledge with Digital Twin must be combined to build what is called Cognitive Twin [88]. Besides, each Digital Twin has different models, which are difficult to identify their interrelationships [89]. Cognitive Twin can solve this problem by linking the knowledge from multiple Digital Twin across several domains. In these domains, combining semantic models with Digital Twin is the core principle to capture complex systems in an intuitive fashion, which can be summarized in standardized ontology languages [90–92]. More sophisticated techniques like knowledge graphs are used to speed up the implementation of Digital Twin [93, 94]. It includes cognition elements, such as reasoning, planning, and learning [95, 96]. However, many gaps remain to be bridged, such as the absence of a logical implementation framework and the integration of empowering technologies and instruments. This subject requires additional research efforts.

5. Research Limitations and Future Studies

While this study contributes to the body of knowledge, it also has limitations. Although a comprehensive search was conducted for relevant material, not all search terms were likely found. Only Scopus, Web of Science, and Google Scholar databases were utilized. Consequently, more papers about the deployment of Digital Twin in the AEC-FM industry have not been addressed. Since the research has these limitations, the results may not accurately represent the literature on Digital Twin applications in the AEC-FM industry. Subjective evaluations may have been applied in the study to find the most relevant publications and identify their use in various lifecycle phases of the literature. In addition, new natural language processing advances are necessary to automatically avoid duplication from various
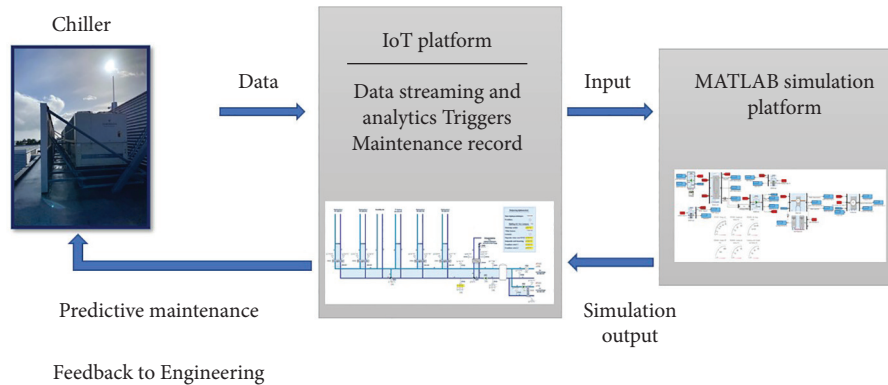
FIGURE 11: Digital Twin predictive maintenance framework of a chiller.

databases, gathering data from all languages and encapsulating them to provide a picture of research from a worldwide perspective. The limitations mentioned above generate grounds for further research and should be considered when interpreting the research findings.

6. Conclusion

The transition to a new era of digital information in the AEC-FM industry comes with Digital Twin technology. Based on the literature review, there are already efforts to implement the Digital Twin concept in the AEC-FM industry. However, these efforts seem to be in a preliminary stage. Much research is needed to successfully add a full-scale high-fidelity Digital Twin model to the AEC-FM industry. Additionally, there seem to be parallel efforts to upgrade BIM to involve the operation and management phase by implementing Digital Twin to the AEC-FM industry. It seems that BIM has the benefit of already being implemented for many assets, even though there are challenges with integrating BIM and IoT and processing the accumulated data. Digital Twin has the benefit of having a good foundation for data processing and integrating BIM. However, the Digital Twin technology is further behind regarding research and implementation in the AEC-FM industry.

Digital Twin research in the AEC-FM industry saw a significant upswing in 2019. Despite being associated with many issues, such as sharing data limitations, project inefficiencies, and the absence of a collaborative approach throughout the lifespan, the implementation and adoption of Digital Twins are expected to grow. This article dealt with the developments in the AEC-FM industry's Digital Twin research and suggested future research paths by doing a scientometric analysis and mapping.

Automation in Construction, Applied Sciences, Engineering Construction, and Architectural Management is the most influential journal in Digital Twin for the AEC-FM industry. The keyword clusters from scientometric analysis results suggested that there are six mainstream research fields in which the AEC-FM industry is studied "Digital Twin in Facility Lifecycle Management," "Digital Twin-Information Integration Standards," "Digital Twin-Based Occupants-Centric Building Design," "Digital Twin-Based Predictive Maintenance," "Semantic Digital Twin for Facility Maintenance," and "Digital Twin-Based Human Knowledge."

Analysis and mapping demonstrated that it is essential to enhance prediction and knowledge integration, occupants' comfort, ontologies, and human-based technologies across the project lifecycle in the near future.

Future research should include a comprehensive viewpoint to deal with the difficulties mentioned in the study. The AEC-FM industry stakeholders and academics will all benefit from the results of this research, which serves to broaden the awareness of present research goals, research gaps, and long- and short-term future research trends in the field of Digital Twin research.

While the study had a limited sample of sources, the data gleaned from them was subject to bibliometric limitations. In addition, only academic research is utilized in scientometric mapping and analysis. It means that practical and commercial innovations are excluded. To gather better findings, future research may use data from practitioners and businesses.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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