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Enabling Technologies and Recent Advancements of Smart Facility Management

Hosam Olimat, Hexu Liu * and Osama Abudayyeh

Department of Civil and Construction Engineering, Western Michigan University, Kalamazoo, MI 49008, USA; hosammuhsentawfiq.olimat@wmich.edu (H.O.); osama.abudayyeh@wmich.edu (O.A.)
* Correspondence: hexu.liu@wmich.edu

Abstract: With various emerging technologies and integration possibilities, smart facility management has gained wide interest in recent years. Several technologies were introduced to support facilities management and improve decision-making, such as Building Information Modeling (BIM), Internet of Things (IoT), Digital Twin (DT), artificial intelligence (AI), and blockchain. Yet, facility managers still face challenges related to data handling and the actual implementation of these technologies. Thus, this paper explores the trends and integration possibilities of smart facilities management technologies to provide a deeper understanding of the current research state and the areas for future exploration. The Scopus database is utilized to collect literature data, and a bibliometric analysis is conducted on 7236 publications of different types, including conference publications, articles, reviews, and book chapters, using VOSviewer software. The results revealed a noticeable growth in the annual number of publications related to this field after 2018. BIM, IoT, and DT were seen to share the greatest research attention, with BIM being the dominant technology. With recent wide attention, blockchain technology is noticed to be introducing many integration possibilities. In addition, the prominent contributing authors, countries, and sources to this research area are also identified.

Keywords: facilities management; smart technologies; operational decision making; predicative maintenance; preventive maintenance; intelligent building; BIM; internet of things; digital twin; blockchain

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1. Introduction

1.1. Facility Management

Throughout the life cycle of construction projects, several phases are involved in delivering and maintaining the infrastructure product. Each phase has different challenges and cost triggers based on the project size. Previous research shows that the total cost of a project over its lifetime is triple the construction costs and seven times greater than the initial investment costs. These costs incur primarily in the operation and maintenance phases [1,2]. Thus, facilities management is crucial when it comes to the life cycle of an establishment. By definition, managing and maintaining facilities is a means of supporting and maintaining the performance of structures to meet the strategic objectives of an organization in varying environments [3]. In addition, facility management plays a vital role in extending the life cycle of an establishment by integrating individuals, locations, processes, and technology in performing the support functions to the core of the establishment [4,5]. Nevertheless, organizations need to embrace innovation and continuous development of the most advanced technological solutions to have successful facilities management and keep the business sustainable [6,7]. In this context, facilities management has been gaining popularity as an area of study in recent decades [8,9].

On the other hand, data are considered the most important base to provide efficient operation and maintain the establishments during facilities management [1,10]. However, data update and exchange have been one of the key challenges when it comes to the different phases of a building's life cycle; extensive research efforts were performed to investigate technological integrations for the construction industry during the past three decades [8,11]. Also, the increasing competition in modern economies, combined with rapid technological breakthroughs, has prompted the construction industry to implement effective supporting systems to assure long-term building functionality [12]. However, the construction sector is still argued to have a slow pace of digitization in asset management terms, where a significant amount of data necessary for operation and maintenance is still maintained in paper documents [7,8,13].

1.2. Digital Technologies

Starting from the evolution of Computer-aided Design (CAD) in the 1970s, several digital technologies were introduced to support facilities management and improve communication. The concept of Building Information Modeling (BIM) in the early 1990s prompted the development of a solid base for decision-making. With a 3D visualization of the establishment, which includes its physical and functional characteristics, BIM is an effective source of data to plan and manage building maintenance [14]. However, without additional data sources, BIM often merely provides static information about the constructed environment and is unable to synchronize real-time data regarding the facility and its users in the models [11]. Despite this, BIM can make operational workflows of facilities management more efficient when combined with modern technologies [15]. As a result, emerging technologies such as Internet of Things (IoT) provided the ability to link networks of sensors to 3D models and generate real-time data streams. Consequently, it advances the performance of building management by linking tangible objects with digital entities to help in asset tracking, problem visualization, and decision-making [16]. Moreover, BIM–IoT integration established the core of a new technology called Digital Twin (DT). A 3D virtual twin that mimics the objects it represents through IoT devices. DT enables real-time detection of issues by keeping an eye on the entire system. DT results in a huge amount of data that often exceeds humans' ability for processing; as such, Artificial Intelligence technology can be utilized to harness these data and deliver facility managers with intelligent control recommendations and predictions [17–19].

In addition to these technologies, several other smart technologies have been found to be employed or integrated by researchers to improve the outcomes of facilities management. Augmented and Virtual reality (AR/VR) represents examples of these promising techniques. With their ability to present and interact with virtual information, AR and VR offer facilities professionals many advantages and possibilities, including the chance to participate in design decisions before the start of the construction, thus reducing 20% of the maintenance problems that result from decisions made during the design [20]. Moreover, AR and VR can be used to improve maintenance efficiency through training and work scenario simulations [21]. Another example is the emerging technology of Blockchain that gained wide construction research interest recently. It was first introduced in cryptocurrencies (i.e., Bitcoin) to keep track of transactions and guarantee their safety. Blockchain provides a decentralized network database with hashing and consensus algorithms and protocols that ensure secure data storage and exchange [22]. The blockchain ledger is considered to be immune to hacking or change as the information on all systems sharing the ledger would have to be changed as well [23]. Thus, this opens a wide range of applications for facilities management, including tracing the history of asset information back to its source by integrating with BIM, managing its supply chain, and securing its transactions with smart contracts [24].

With these described technologies and the growing research efforts to innovate facilities management processes, there is a need to stay on top of new innovations and gain a deeper understanding of the current state of research in the field of smart facilities management [7,8,25]. Thus, by analyzing the existing literature, the bibliometric study can reveal the most influential authors, countries, sources, and research topics, as well as identify areas for future exploration. Consequently, this will accelerate the adoption and implementation of these technologies in future efforts for growth and development in smart facilities management.

2. Research Goals and Methodology

As mentioned earlier, smart facility management has been gaining wide interest in recent years, with several technologies introduced to support facilities management operations and improve decision-making. As a result, this research aims to quantitatively explore the domain knowledge of smart technologies for facilities management, its trends and needs, and its most influential contributors.

By achieving these research goals, researchers will be able to discover the connections between the smart technologies, identify potential areas for future research, and make informed decisions about which smart technologies and trends should be focused on. This research contributes to the body of knowledge by providing a clearer understanding of the current state of the research regarding the implementation and integration possibilities of these technologies toward smart facility management.

The research goals are attained through the following steps:

(1) A data collection that involved retrieving, screening, and refining the literature from the Scopus database that was published between 2012 and 2023 on smart technological solutions for facility management.
(2) A bibliometric analysis via VOSviewer software to visualize this knowledge field and examine its articles, sources, and keywords relationships, as well as the areas for future exploration.

2.1. Data Collection

The initial step in the review process was a literature search and data collection of relevant technology documents related to facilities management published between 2012 and 2023. The selected period allowed for an adequate study period to assess all state-of-the-art technologies and solutions. The Scopus database was utilized as the main source of information due to its broad coverage of construction, interdisciplinary, and journal publications [22]. In addition, Scopus is considered the world's largest abstract and citation database, and it ensures a comprehensive collection of information related to the topic of study [8]. Figure 1 describes the procedure followed to reach the final set of publications employed in the analysis.

To comprehensively identify relevant publications pertaining to facilities management, several keywords were applied in the search. These keywords included "facilities management", "building management", "asset management", "facility management", "building maintenance", "operation and maintenance", "O&M", and "O and M". The reason for using general keywords was multiple-fold, including (1) the objective of this research was to identify various applications of these technologies in facilities management, (2) most of the literature includes specific facility zones and our selected keywords, and (3) since the application of these technologies spread to include various zones of asset management and decision making, it might not be possible to include all these zones. Given this, the keywords were selected in the literature search. All related literature was retrieved by searching within the title, abstract, and keywords sections. The search was performed in January 2023 with a date range set from 2012, providing a sufficient study period to analyze all state-of-the-art technologies. This resulted in the identification of 30,522 documents, with only 28,763 of them being in English.

Following the keywords search, a literature screening was performed. The research team used a thorough strategy to review and evaluate the literature. At the beginning, the authors conducted the review and evaluation individually by assessing the relevance of the literature under each Scopus filter separately; then, we worked in a focus group that intended to evaluate each member's findings, perceptions, and insights. In the focus group, the team employed a frequent combination of review sessions to compare and discuss the similarities and discrepancies between their selection results. Thus, after several focus group meetings, the team's collaborative efforts in integrating the diverse viewpoints and merging the individual findings helped ensure the inclusion of the most recent and relevant sources. As shown in Figure 1, the first screening step involved limiting the resulting documents to only four subject areas, including engineering, computer science, decision sciences, and multidisciplinary. Thus, documents outside facilities management technology solutions and decision-making were excluded, resulting in 8465 publications. Furthermore, the publications were further screened by eliminating some source titles that had non-related documents to the targeted research, such as IEEE International Symposium On Industrial Electronics, IEEE Transactions On Dielectrics And Electrical Insulation, and Ecs Transactions. This screening step was performed following the methodology of [22] by examining the publications of the source titles since 2012 for relevance to smart facilities management technologies in decision-making. The source titles identified by Scopus results were analyzed, and the evaluation of the research team excluded 100 documents. As a result, the number of publications was reduced to 8365 documents.

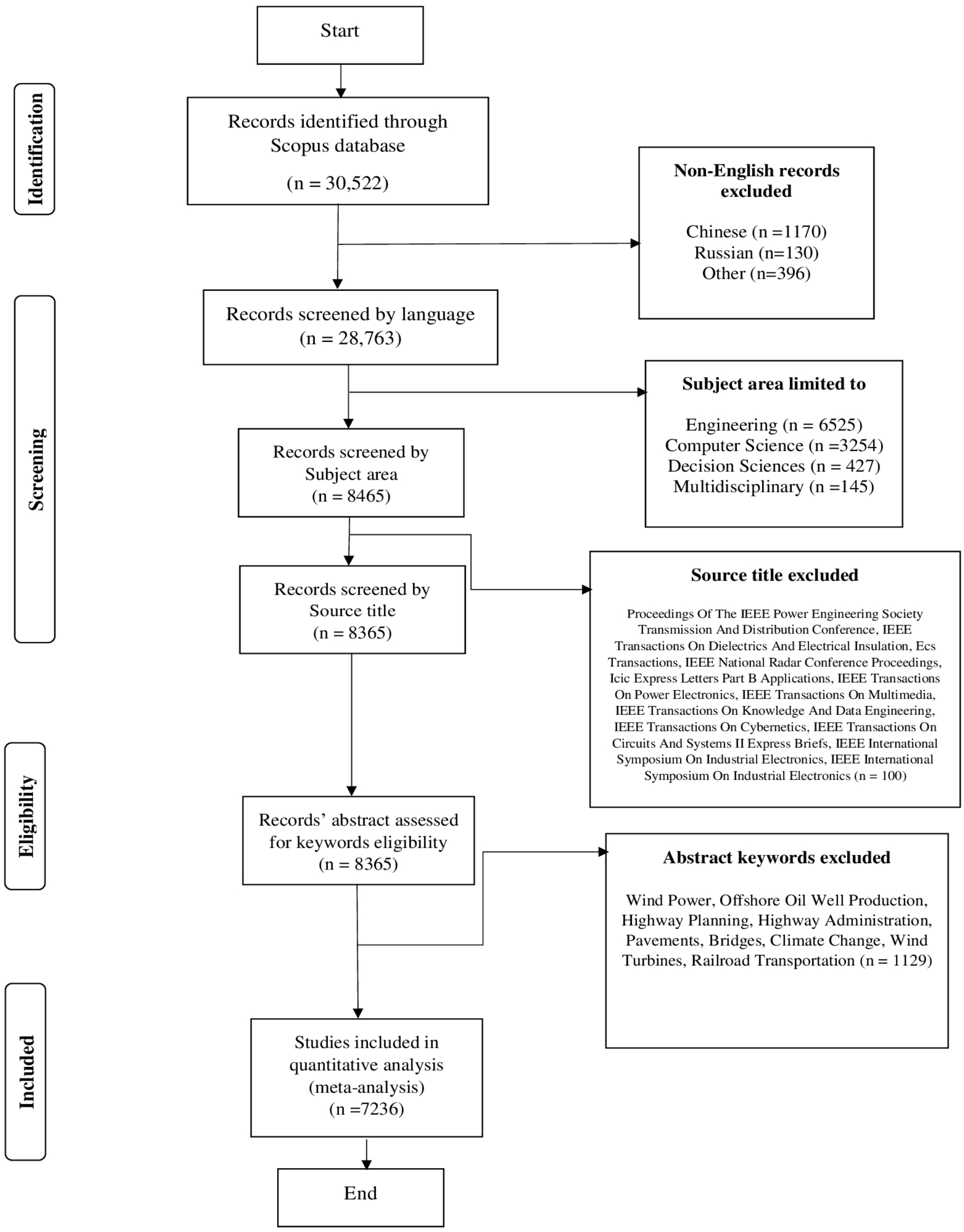

Figure 1. Data collection steps.

In order to better ensure the quality and relevancy of the data set, a final eligibility screening was performed based on keywords present in the abstracts. We utilized Microsoft Excel as our primary tool. Excel allowed us to record, categorize, and analyze the collected literature. Abstracts containing keywords associated with non-relevant topics, such as highway administration, bridges, railroad transportation, and offshore oil well production, were excluded. This resulted in a total of 7236 publications that were deemed to be suitable for analysis using VOSviewer version 1.6.18.

2.2. Quantitative Trend Analysis

Bibliometric analysis is a science mapping and visualizing technique that analyzes the structural and dynamic characteristics of a research field using statistical techniques. It is implemented in the field of scientometry to explore knowledge domains and links between publications, journals, and keywords [22,26]. Thus, the analysis can be used to discover trends and topics of interest and identify gaps in the research domain. As a result, the quantitative trend analysis (i.e., bibliometric analysis) performed in this research for science mapping included multiple types of quantitative analyses that shed light on exploring all research objectives utilizing VOSviewer software and Excel counting functions. In more detail, the first analysis among the five performed was the co-occurrence of author keyword analysis, which highlighted the current research trends and connections, and provided insight into research difficulties and future needs based on the core content of publications represented by their keywords. Second was the co-authorship of authors and countries analysis, which helped map the research landscape by providing a conceptual image of the prime contributors, research networks, and collaboration patterns in the knowledge field in terms of authors and countries. Moreover, institutions and outlet analyses were two other analyses conducted to map the research landscape; they aimed to evaluate the institutions and journals with the highest number of contributions in a certain research field, thus identifying the current most leading sources of knowledge. Lastly was citation analysis, which analyzed the significance and impact of the publications with the highest influence. This consequently provided indicators regarding research patterns and major topics in the knowledge field.

A large number of publications were recommended while performing bibliometric analysis. In this research, citation, abstract, and keywords information of the 7236 documents were exported from Scopus as a CSV file and imported to VOSviewer software. However, data cleaning was needed to merge the keywords with the same semantic meaning before running the analyses and generating the networks. Thus, all keywords generated by the software were identified, arranged alphabetically, and analyzed for their semantic meaning. In addition, a text thesaurus file containing all collected keywords with the same meaning along with the normalized term assigned to each one was created and then imported to the VOSviewer software before running the analysis to merge these keywords. For example, “bim technology”, “building information model”, and “building information modeling” were all normalized under the term “bim”. Another example is “blockchain technology” and “blockchain”. After cleaning all keywords, two types of analyses were conducted utilizing the software, including the co-occurrence of author keyword analysis and co-authorship of authors and countries analysis. In the first analysis, a network of interconnected nodes with different colors and sizes was produced to demonstrate the research trends and focus. Each node represented a keyword, with its size being proportional to its occurrence frequency in the literature keywords (i.e., having a larger node implied a high number of occurrences for the keyword). On the other hand, different colors were utilized to represent different research clusters, where all nodes with the same color presented a research trend, as their keywords frequently occurred together. In addition, the connections between the nodes were called links. The thickness of the links donated the frequency of connections between the nodes (i.e., thicker links implied a stronger connection). With this information, this analysis was able to provide insights into the major research trends, researchers’ interests, and how different research topics are intellectually connected [22]. The second analysis had the same structure as the first one, except that the nodes represented the authors or the countries associated with the literature. This generated quantitative details to describe their activity and productivity on a certain research topic, their number of citations, and their interconnection together in certain research topics [26]. The remaining analyses (i.e., Citation analysis, Institutions analysis, and Outlet analysis) were performed manually using the retrieved dataset and Excel counting functions.

3. Bibliometric Analysis Results

3.1. Overview

Figure 2 represents the annual distribution of publications around technology and smart advancements in facilities management over the last ten years. From the figure, it was noticed that before 2018, the number of publications fluctuated between a minimum of 504 and a maximum of 626. However, going from 2019 until 2022, there was a high growth that averaged almost 800 publications per year, which is about 200 publications higher than the average of the years before. Thus, the figure indicates that research efforts are expanding lately towards adopting more technological solutions to advance and improve facilities management performance. This can be assumed to be a result of the growing attention to expanding the benefits of Building Information Modeling (BIM) beyond the construction phase. Additionally, the emergence of new technologies such as DT and the new upcoming technology of blockchain resulted in increasing researchers' interest in integrating and utilizing innovative solutions to produce smarter maintenance systems.

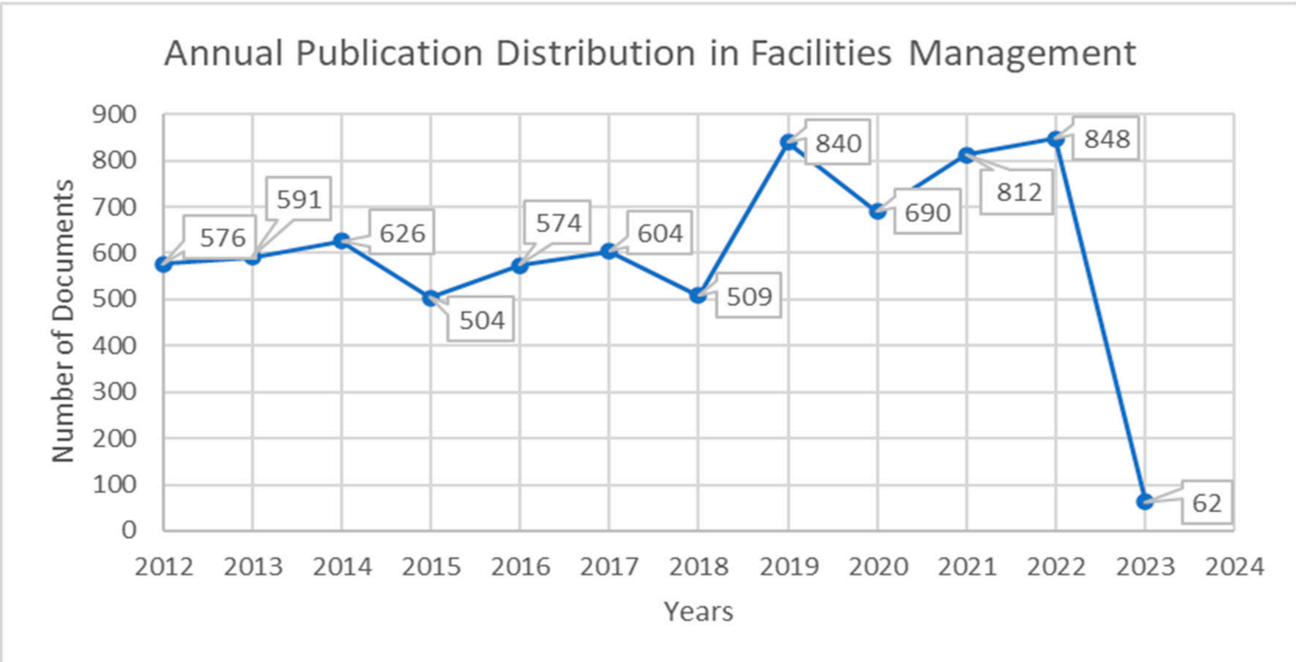

Figure 2. Annual facilities management publication distribution.

3.2. Co-Occurrence of Author Keywords

After running the VOS model with the retrieved Scopus publications, cleaning the data for the same keywords' semantic meaning, and identifying the threshold to be higher than 15 occurrences, a total of 92 nodes (keywords) were used to build the network, as shown in Figure 3.

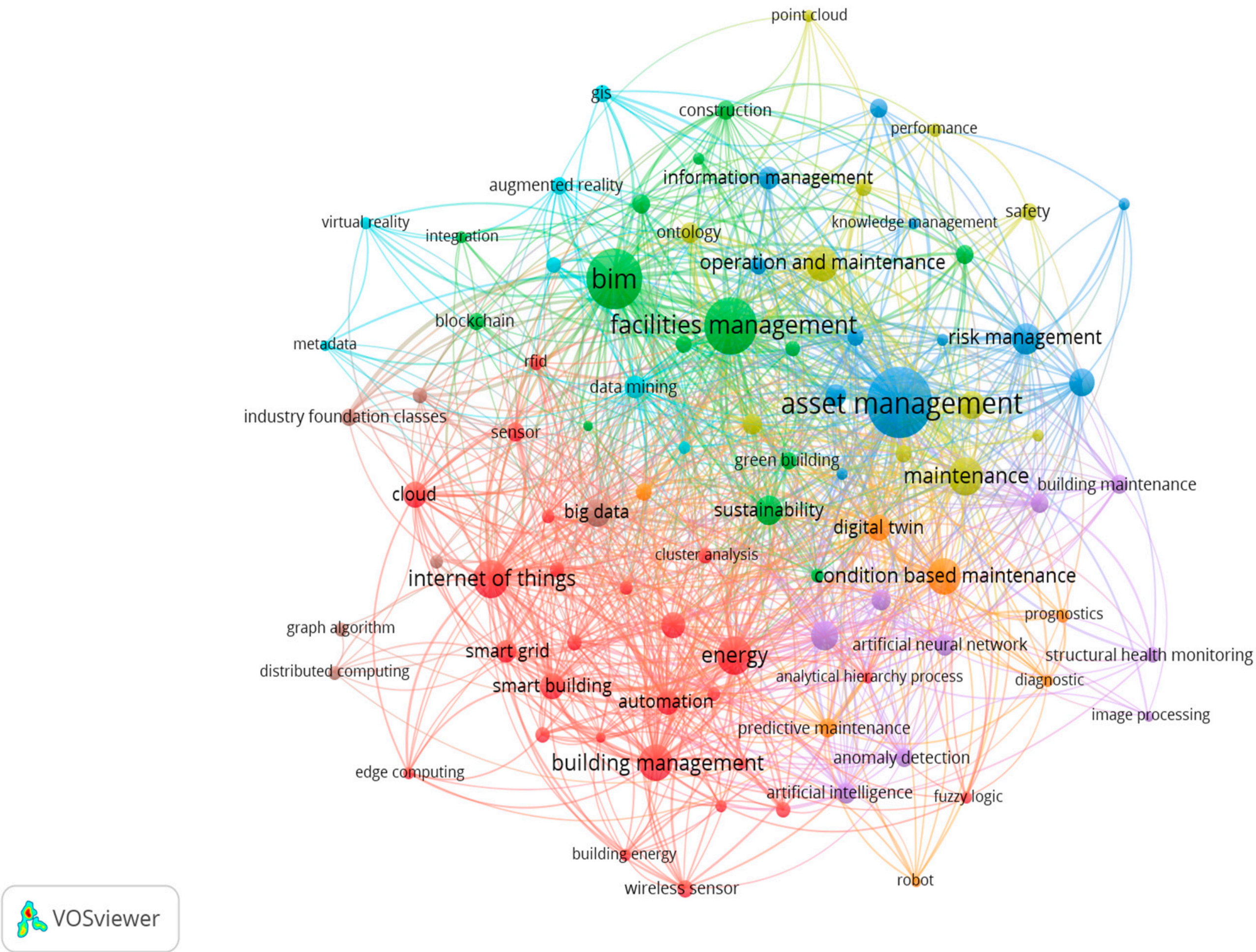

Figure 3. Co-occurrence of author keyword network map.

After being arranged based on the number of occurrences, Table 1 summarizes the statistics of the keywords, including the number of links, occurrences, average publication year, and average citations. A clustering analysis of the keywords was performed to group the most related and same-trend keywords together. These clusters are presented in the network map with different colors to display the research focus. As a result, eight clusters were built, including BIM life-cycle integration and blockchain, Internet of Things and smart building, asset and knowledge management, artificial intelligence and decision making, augmented reality and visualization, digital twin, interoperability, and preventive maintenance.

Table 1. Keywords included in the co-occurrence network.

ID	Label	Links	Occurrences	Average Publication Year	Average Citations
1	asset management	76	577	2017	7
2	bim	77	432	2018	24
3	facilities management	74	372	2018	18
4	maintenance	66	177	2017	8
5	energy	56	176	2017	15
6	internet of things	63	167	2019	13
7	building management	54	160	2017	14

Table 1. *Cont.*

ID	Label	Links	Occurrences	Average Publication Year	Average Citations
8	condition based maintenance	48	154	2017	11
9	operation and maintenance	47	143	2018	7
10	risk management	42	117	2016	5
11	machine learning	51	104	2020	9
12	sustainability	40	99	2017	8
13	reliability	44	94	2017	8
14	big data	48	89	2019	8
15	maintenance management	37	88	2018	8
16	cloud	33	85	2017	11
17	smart building	50	82	2018	24
18	digital twin	42	80	2021	8
19	fault detection	45	79	2018	20
20	automation	46	67	2018	10
21	smart grid	35	64	2016	10
22	information management	33	63	2018	13
23	data mining	48	62	2018	10
24	optimization	32	60	2018	11
25	monitoring	39	54	2017	4
26	deep learning	25	52	2021	10
27	artificial intelligence	30	51	2020	7
28	artificial neural network	33	50	2019	11
29	ontology	29	49	2018	19
30	building maintenance	17	48	2018	11
31	anomaly detection	27	47	2019	6
32	construction	30	47	2018	21
33	infrastructure management	23	47	2018	8
34	predictive maintenance	34	47	2020	9
35	life cycle	28	46	2018	11
36	decision making	35	45	2019	8
37	sensor	32	45	2017	18
38	management	27	44	2018	4
39	blockchain	13	40	2021	5
40	augmented reality	19	39	2018	22
41	decision system	34	39	2018	16
42	industry 4.0	28	38	2021	6
43	simulation	26	38	2018	9
44	gis	23	37	2018	9
45	green building	23	37	2018	18
46	industry foundation classes	22	37	2018	27
47	database	20	36	2017	6

Table 1. *Cont.*

ID	Label	Links	Occurrences	Average Publication Year	Average Citations
48	safety	20	36	2018	6
49	wireless sensor	19	36	2016	11
50	inspection	25	35	2018	7
51	cost analysis	19	34	2016	11
52	interoperability	23	33	2017	13
53	data analysis	30	32	2018	12
54	hvac	22	32	2017	27
55	life cycle cost	27	32	2018	9
56	structural health monitoring	12	32	2019	8
57	intelligent building	24	30	2016	9
58	rfid	16	30	2016	7
59	visualization	25	30	2019	14
60	cluster analysis	20	28	2019	8
61	smart city	25	28	2019	22
62	cyber physical systems	25	27	2019	13
63	graph algorithm	7	25	2019	7
64	pattern recognition	13	25	2017	15
65	prognostics	16	25	2018	32
66	thermal comfort	18	25	2018	19
67	building performance	16	23	2018	23
68	performance	14	23	2017	6
69	security	21	23	2018	8
70	distributed computing	8	22	2018	12
71	edge computing	11	21	2021	4
72	fuzzy logic	15	21	2016	12
73	project management	15	21	2017	26
74	diagnostic	15	20	2017	16
75	virtual reality	18	20	2019	22
76	bayesian network	17	19	2019	16
77	building energy	14	19	2019	19
78	integration	19	19	2017	37
79	point cloud	12	19	2018	38
80	energy saving	15	18	2017	8
81	preventive maintenance	17	18	2018	8
82	support vector machine	17	18	2017	14
83	analytical hierarchy process	13	17	2019	6
84	forecasting	17	17	2019	4
85	knowledge management	15	17	2016	8
86	reliability assessment	9	17	2017	2
87	image processing	8	16	2017	17
88	metadata	13	16	2017	16

Table 1. *Cont.*

ID	Label	Links	Occurrences	Average Publication Year	Average Citations
89	cyber security	21	15	2018	4
90	indoor environmental quality	16	15	2018	14
91	renewable energy	17	15	2018	6
92	robot	13	15	2019	3

3.2.1. BIM Life-Cycle Integration and Blockchain (Green Cluster)

As shown in Table 1 and Figure 3, this cluster had the highest number of occurrences (432), the strongest link (i.e., a link of 77), and the closest distance to facilities management keywords, which indicates that BIM had strong connections to facilities and other keywords in the field. Additionally, the cluster reflects the amount of research efforts put in to address the benefits and the challenges of utilizing BIM past the construction phase to the operation and maintenance phase, resulting in keywords such as "bim", "life cycle", "sustainability", and "construction" as shown in Table 2, which summarizes this cluster. BIM's importance comes from the fact that maintaining and operating a structure highly depends on precise and reliable data. These data are usually transferred in an unorganized manner after the construction phase, resulting in extensive efforts and error-prone practices. Thus, the integration of BIM and facilities management can help connect the gap with the early stages of a project's life cycle, if implemented properly [5,7,27]. As a result, the significance of the BIM–FM integration and its ability to provide up-to-date and accurate as-built data, simpler data access and retrieval, and its 3D visualization explain the extensive interest this topic has gotten in the past few years. However, even though numerous publications have recorded cases of effective integration for certain facilities management areas, they still experience many tangles in information identification, preparation, storage, exchange, and sharing when it comes to implementing BIM technology [5,27].

Table 2. BIM life-cycle integration and blockchain cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
BIM Life-Cycle Integration and Blockchain	2	bim	77	629	432	2018
	3	facilities management	74	488	372	2018
	12	sustainability	40	109	99	2017
	32	construction	30	63	47	2018
	35	life cycle	28	63	46	2018
	38	management	27	48	44	2018
	39	blockchain	13	21	40	2021
	45	green building	23	45	37	2018
	51	cost analysis	19	26	34	2016
	55	life cycle cost	27	38	32	2018
	67	building performance	16	30	23	2018
	73	project management	15	33	21	2017
	78	integration	19	32	19	2017
	91	renewable energy	17	17	15	2018

On the other hand, as shown in Table 2, blockchain technology (with 40 occurrences) was also mentioned in this cluster with keywords such as "integration", "cost analysis", and "life cycle cost". This emphasizes the technology's ability to integrate with other technologies and provide secure transactions. This new technology was first used in cryptocurrency transactions, mainly Bitcoin, as it provides a decentralized network for safe data exchange and storage. Consequently, its hashing and consensus algorithms, protocols, and resistance against tampering and modification attracted researchers to create models to adopt the technology outside the field of cryptocurrency. In construction, many research articles suggested employing blockchain in areas such as smart contracts, supply chains, and BIM to lower transaction costs, keep track of goods and services, and maintain records and documents [22,28]. Moreover, having blockchain and BIM in the same cluster indicates the technologies' capability to integrate and improve the data share and delivery process from the construction to maintenance phases [28,29]. In addition, BIM–blockchain integration can help fill the gap of error-prone data transfer by ensuring data integrity, accuracy, and transparency and being an untampered source of truth in construction projects [22,30]. However, since the average publication year was 2021 for blockchain keywords, it is emphasized that it is still a new technology to be studied in the facilities management area, where it will need more case studies and actual implementations to explore its efficiency and ability to be an innovative solution for the current gaps.

3.2.2. Internet of Things (IoT) and Smart Building (Red Cluster)

The keywords "Internet of Things" and "Smart building" had an occurrence of 167 and 82, respectively, making them the second largest cluster in the network, as shown in Table 1 and Figure 3. In addition, their connections to other keywords, with links of 63 and 50, were among the highest in all clusters, indicating their significance in the current research trends. Furthermore, this cluster had the highest number of keywords relating together with a total of 26 keywords, where Table 3 presents the first 15 keywords with the highest occurrences in this cluster. Examples of these keywords include "rfid", "pattern recognition", "wireless sensors", "fault detection", "edge computing", and "cyber physical systems", thus showing the diversity of techniques being applied to improve IoT technology processes. On the other hand, the keyword "energy" being the highest among all keywords in this cluster, reflects the importance of energy management and optimization, especially in smart buildings, and the connection with IoT devices that help reduce energy consumption and cost. Moreover, the research on energy consumption has been increasing since the COVID-19 epidemic, as it indirectly helped to drive down consumption by compelling most organizations to cut down their operations [31].

By definition, IoT is a modern technology that utilizes intelligent devices (e.g., sensors, cameras, and smartphones) intended to monitor, capture, share, and react to changes in the environment [7,32]. In facilities management, the technology has been used to provide automation and real-time information regarding the condition of the facility, predict the risk status of various building components, and suggest certain solutions while storing the data in the cloud for users to monitor remotely [7,33]. IoT's strong connection to the keywords "smart building", "smart city", and "smart grid" reflects the emerging efforts (i.e., average publication year of 2019) to digitalize asset management and improve its efficiency. In detail, the concept of smart cities involves employing IoT technologies to improve quality of life by delivering smart systems such as intelligent transportation systems, environmental monitoring, smart services, energy monitoring, and crowdsensing, which can be reflected in a more confined space and called smart building [34,35]. In addition, the integration of robotic devices with the principles of IoT and artificial intelligence establishes the term Internet of Robotic Things (IoRT) [36], thus constructing a smart network of interconnected devices capable of communicating quick judgments, cooperating with surrounding processes, and performing unanticipated tasks autonomously [36]. An IoRT network integrates several tools to support decision-making processes, including geospatial simulation and sensor fusion, which help in enhancing the perception, optimization, analysis, and visualization of data [36]. Moreover, visual perception and environment mapping algorithms are other important components of IoRT, as they are employed to effectively diagnose and handle issues from the gathered data and to extract meaningful information about the surrounding environment [37]. Nevertheless, being a relatively new technology in facilities management, IoT applications are still improving with time, especially with smart systems development and the current integration challenges with technologies such as BIM, DT, augmented reality, and blockchain, which make it a hot topic for future trends.

Table 3. Internet of Things (IoT) and smart building cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Internet of Things and Smart Building	5	energy	56	222	176	2017
	6	internet of things	63	287	167	2019
	7	building management	54	208	160	2017
	16	cloud	33	84	85	2017
	17	smart building	50	148	82	2018
	19	fault detection	45	76	79	2018
	20	automation	46	113	67	2018
	21	smart grid	35	95	64	2016
	49	wireless sensor	19	46	36	2016
	53	data analysis	30	44	32	2018
	54	hvac	22	49	32	2017
	57	intelligent building	24	46	30	2016
	58	rfid	16	31	30	2016
	60	cluster analysis	20	26	28	2019
	61	smart city	25	48	28	2019

3.2.3. Asset and Knowledge Management (Dark Blue Cluster)/Preventive Maintenance (Yellow Cluster)

In this cluster, keywords such as “risk management”, “information management”, “optimization”, “forecasting”, “reliability”, “decision system”, “inspection”, and “preventive maintenance’ all connect together to form two clusters that represent the research efforts towards optimizing and improving the process of utilizing information to make effective and preventive decisions. As a result, the combination of these clusters formed the third-highest cluster in the network, as shown in Figure 3. In addition, both Tables 4 and 5 sort clusters’ keywords by the number of occurrences. The average publication year of the cluster was 2018. It contained keywords with links that ranked among the highest links in the network (i.e., risk management 42, and reliability 44), which implies that information management to optimize maintenance decisions with different techniques such as simulation, forecasting, and risk and reliability assessments is an important topic for improvement by researchers. In addition, it was noticed that the process of handling maintenance data to make effective decisions is moving forward with the development of technologies such as BIM, IoT, DT, machine learning, and artificial intelligence, as most keywords in this cluster connect to these technologies. This makes the decision process less time-consuming, more efficient, and more accurate than before. In general, this cluster describes the main idea behind facilities data management, which is making the best use of gathered information to protect assets and extend their useful life.

Table 4. Asset and knowledge management cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Asset and Knowledge Management	1	asset management	76	614	577	2017
	10	risk management	42	144	117	2016
	15	maintenance management	37	113	88	2018
	22	information management	33	79	63	2018
	24	optimization	32	62	60	2018
	33	infrastructure management	23	54	47	2018
	41	decision system	34	69	39	2018
	43	simulation	26	48	38	2018
	82	support vector machine	17	22	18	2017
	84	forecasting	17	22	17	2019
	85	knowledge management	15	22	17	2016
	86	reliability assessment	9	20	17	2017

Table 5. Preventive maintenance cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Preventive Maintenance	4	maintenance	66	248	177	2017
	9	operation and maintenance	47	160	143	2018
	13	reliability	44	101	94	2017
	25	monitoring	39	72	54	2017
	29	ontology	29	77	49	2018
	47	database	20	30	36	2017
	48	safety	20	35	36	2018
	50	inspection	25	48	35	2018
	68	performance	14	25	23	2017
	79	point cloud	12	22	19	2018
	81	preventive maintenance	17	20	18	2018

3.2.4. Digital Twin (Orange Cluster)

As shown in Figure 3 and Table 6, this cluster presents the fourth-largest cluster with an occurrence frequency of 80. The cluster is made out of the keywords "diagnostic", "industry 4.0", "predictive maintenance", "prognostics", "condition based maintenance", and "robot", which all reflect the concepts behind this emerging technology by monitoring the conditions of the assets to predict and prevent systems failure. In general, for building assets, the digital twin basis represents an integration between BIM and IoT technologies to create a virtual 3D representation of the asset with real-time sensing data visualization and monitoring [8]. The applications of this technology have been improving since it was first developed. Thus, this cluster has a strong connection with the keywords "internet of things" and "machine learning" (i.e., link strength of seven and five, respectively), which implies the high interest of researchers in improving the real-time monitoring and performance prediction of the technology that can lead to the automation of decision making, which will enhance predictive maintenance and prognostics processes [10]. However, full automation of decision-making is not there yet, as human control over the final decision based on the collected data is still needed for most of the relevant studies [11]. This can be explained based on the fact that the average publication of this cluster is 2021 and that no research was made about DT in facilities management before 2016 [18]. Consequently, more research is expected in the future with the continuous development of IoT, artificial intelligence, and industry 4.0 tools to fill the current gaps and encourage facilities management to adopt DT in their systems.

Table 6. Digital twin cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Digital Twin	8	condition based maintenance	48	183	154	2017
	18	digital twin	42	147	80	2021
	34	predictive maintenance	34	103	47	2020
	42	industry 4.0	28	76	38	2021
	65	prognostics	16	37	25	2018
	74	diagnostic	15	28	20	2017
	92	robot	13	26	15	2019

3.2.5. Artificial Intelligence and Decision Making (Purple Cluster)

Being a relatively new cluster (Average publication year 2020), Artificial Intelligence (AI) and its applications in facilities management are interesting topics when it comes to decision-making for researchers. Using algorithms, AI tools can detect patterns, relationships, and correlations between information based on a unique multidimensional data source [38]. The keywords contained in the cluster, including "deep learning", "machine learning", "image processing", "artificial neural network", and "anomaly detection" all describe techniques utilized in AI technology to process and automate maintenance information. Moreover, as shown in Table 7, it was noticed that the keyword "machine learning" had one of the highest links in the network (51 links), along with ranking among the largest nodes (104 occurrences). In addition, both deep learning and artificial neural network, which are both branches of machine learning, had a high number of occurrences in this cluster (52 and 50, respectively). Additionally, from other clusters, Bayesian network and support vector machine with 19 and 18 occurrences, respectively, were present with other technologies, which are also part of machine learning. Thus, this implies that the current research trends in facilities management and AI are highly dependent on the machine learning branch, with the research focus on the field of supervised learning to improve decision-making. As a result, most cluster keywords strongly connect to other technologies implemented in facilities management, such as BIM, IoT, DT, and augmented reality, combining data collection and data science to generate accurate solutions. These integrations can result in an intelligent maintenance system that is able to identify building components, automate performance assessment of facilities, detect possible risks, have real-time learning, and perform predictions [39,40]. In general, this topic is still under future development for further integration and case studies, especially with the complexity of maintenance decisions and the number of objectives that need to be considered while making these decisions.

Table 7. Artificial intelligence and decision making cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Artificial Intelligence and Decision Making	11	machine learning	51	147	104	2020
	26	deep learning	25	47	52	2021
	27	artificial intelligence	30	77	51	2020
	28	artificial neural network	33	69	50	2019
	30	building maintenance	17	34	48	2018
	31	anomaly detection	27	50	47	2019
	36	decision making	35	75	45	2019
	56	structural health monitoring	12	26	32	2019
	87	image processing	8	13	16	2017

3.2.6. Augmented Reality and Visualization (Light Blue Cluster)

Several technologies have come together to form this cluster, including Augmented Reality (AR), Virtual Reality (VR), and Geographic Information Systems (GIS). Based on Table 8, AR technology had the highest occurrence frequency in the cluster (i.e., 39) and the second-highest number of links (i.e., 19). Its ability to combine computer information and the real world can provide numerous applications for facility managers, such as training, locating infrastructure positions, and visualizing future plans [21,41]. Moreover, another technology in this cluster is VR, which is similar to AR, except that it provides a virtual view of the world rather than a real view. It has an occurrence frequency of 20 in the network and can be utilized to facilitate maintenance managers' inputs on designs, display visualized project information, and offer effective training [42]. On the other hand, GIS technology had the highest number of links in the cluster (i.e., 23) and the second-highest occurrences (i.e., 37), implying its importance to the research trends of this cluster. Thus, this technology is not new to maintenance management, as it was utilized to manage the external works of facilities, followed by improvements to the technology to provide analyses regarding asset inventories, fire safety reviews, and space usage, availability, and optimization inside buildings [13]. Based on the network, these state-of-the-art technologies were found to have a strong link with either one of the above-mentioned clusters or with all of them, especially BIM, being connected to all. In research, the benefits of these integrations with other technologies offer many advantages for facilities management activities such as safety simulations, process monitoring, space management, and future planning [11,21]. Consequently, these technologies have a great potential for more integrations in the future to improve decision-making by providing enhanced visualization of different types of real information to facility management staff.

Table 8. Augmented reality and visualization cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Augmented Reality and Visualization	23	data mining	48	100	62	2018
	40	augmented reality	19	48	39	2018
	44	gis	23	50	37	2018
	59	visualization	25	49	30	2019
	75	virtual reality	18	30	20	2019
	76	Bayesian network	17	26	19	2019
	88	metadata	13	20	16	2017

3.2.7. Interoperability (Brown Cluster)

The last cluster in this network is Interoperability, as shown in Table 9. The cluster is made of keywords including "distributed computing", "industry foundation classes", "security", "big data", "graph algorithm", and "interoperability". Even though it is the smallest cluster in the network in terms of the keyword's numbers, the keyword "big data" had one of the highest occurrence frequencies in the network (i.e., 89) and a high number of links (i.e., 48). Furthermore, since facilities management is run on several systems and many technologies are seeking integration with large amounts of data, such as BIM and IoT, Interoperability rose as a very important topic with 33 occurrences. In fact, smart environments developed based on BIM and IoT can be obstructed in cases of poorly designed and implemented information integration and management systems [16,43]. As a result, this cluster describes the substantial attention of researchers towards optimizing big data transfer between systems, mapping of data schemas, and decreasing the amount of data losses. Based on the network and Table 9, this cluster and the keyword "industry foundation classes" with 37 occurrences are strongly connected to BIM technology, which is illustrated in the fact that Interoperability is the core of BIM technology and that for BIM data exchange, industry foundation classes is most used file format [44]. Although much research is being conducted to resolve interoperability issues for BIM and IoT, Interoperability is still facing some challenges, such as the varied data schemas for devices, buildings, and cities and many IoT data communication protocols [16,43]. Yet, knowing that the average publication year for Interoperability was 2017 and there are still technology integration possibilities, it is still a work in progress that has been going on for a while. More interoperability solutions are expected in future research.

Table 9. Interoperability cluster.

	ID	Label	Links	Total Link Strength	Occurrences	Average Publication Year
Interoperability	14	big data	48	135	89	2019
	46	industry foundation classes	22	70	37	2018
	52	interoperability	23	60	33	2017
	63	graph algorithm	7	7	25	2019
	69	security	21	29	23	2018
	70	distributed computing	8	11	22	2018

3.3. Citation Analysis

Citations analysis was performed to identify the publications with the highest impact in the technological field of facilities and asset management. Table 10 presents the details of the first ten publications with the highest number of citations from the retrieved documents. It was noticed that seven out of the ten documents were related to BIM, which reflects the significance of this technology in maintenance research, as proved earlier with most of the clusters being connected to it. In addition, the three first most-cited publications on the list (i.e., 1253, 593, and 469 citations) are all part of BIM, as they studied and reported the challenges of implementing BIM technology in existing buildings, potential application possibilities in facilities management along with data requirement challenges, and the use of laser scanning to create 3D BIM models for existing buildings. Thus, BIM technology can be considered to be the fulcrum of technologies in facilities management research. On the other hand, the fourth most-cited document, after BIM publications, with 457 citations, evaluated IoT technical opportunities and challenges in smart buildings, which was expected due to the fact that the IoT cluster was the second most attractive cluster after BIM. Additionally, the seventh publication on the list (Table 10 with 294 citations) was also related to IoT and reviewed its integration with BIM and the areas of application and limitations of this integration. Consequently, IoT and BIM technologies share great attention from researchers in the field of facilities management, especially with the development of DT. Moving down the list, another topic was found to be highly cited, which reviewed AR technology and its application for architecture, engineering, construction, and facility management, where it received a total of 286 citations. Another significant publication was found on the list (number 9) with 250 citations, where a new system was introduced to reduce HVAC energy usage in commercial buildings by employing the building's existing WiFi network and occupants' smartphones.

Table 10. Most cited publications.

Number	Authors	Title	Year	Source Title	Cited by
1	Volk R.; Stengel J.; Schultmann F.	Building Information Modeling (BIM) for existing buildings-Literature review and future needs	2014	*Automation in Construction*	1253
2	Becerik-Gerber, B., Jazizadeh, F., Li, N., Calis, G.	Application areas and data requirements for BIM-enabled facilities management	2012	*Journal of Construction Engineering and Management*	593
3	Xiong X.; Adan A.; Akinci B.; Huber D.	Automatic creation of semantically rich 3D building models from laser scanner data	2013	*Automation in Construction*	469
4	Minoli D.; Sohraby K.; Occhiogrosso B.	IoT Considerations, Requirements, and Architectures for Smart Buildings-Energy Optimization and Next-Generation Building Management Systems	2017	*IEEE Internet of Things Journal*	457
5	Eadie R.; Browne M.; Odeyinka H.; McKeown C.; McNiff S.	BIM implementation throughout the UK construction project lifecycle: An analysis	2013	*Automation in Construction*	435
6	Wong J.K.W.; Zhou J.	Enhancing environmental sustainability over building life cycles through green BIM: A review	2015	*Automation in Construction*	346
7	Tang S.; Shelden D.R.; Eastman C.M.; Pishdad-Bozorgi P.; Gao X.	A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends	2019	*Automation in Construction*	294
8	Chi H.-L.; Kang S.-C.; Wang X.	Research trends and opportunities of augmented reality applications in architecture, engineering, and construction	2013	*Automation in Construction*	286
9	Balaji B.; Xu J.; Nwokafor A.; Gupta R.; Agarwal Y.	Sentinel: Occupancy based HVAC actuation using existing wifi infrastructure within commercial building	2013	*SenSys 2013—Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*	250
10	Motawa I.; Almarshad A.	A knowledge-based BIM system for building maintenance	2013	*Automation in Construction*	234

3.4. Co-Authorship Analysis

In this section, another type of analysis was performed utilizing VOSviewer to evaluate the authors and countries connected with the highest number of documents and citations. This provided a conceptual image of the prime contributors in the technological field of facilities management. Table 11 represents the highest number of documents and citations produced by either a single author or a collaboration of the same authors, along with their average publication year. It was noticed that in terms of the number of documents, authors Yang X. and Ergan S. worked together on four publications, reaching 59 citations with an average publication year of 2015, giving them the highest number of citations and documents in the first group of four documents. On the other hand, for a single author, Ismail A.-A. worked alone on four separate documents, which received a total of 35 citations. In addition, Ismail A.-A.'s documents had an average publication year of 2018, which is the most recent in their category. Furthermore, for three publications, authors Gao X. and Pishdad-Bozorgi P. held a total of 181 citations with an average of 2019, which were considered the highest and most recent in their group. Going down to only two documents, researchers Tang S., Shelden D.R., Eastman C.M., Pishdad-Bozorgi P., and Gao X. collaborated two times to achieve a total of 350 citations, which were considered the most recent documents from all categories (i.e., 2020) and had the highest citations among all categories above them (i.e., more than or equal to two documents). For the last category on the list, the authors of the document "Building Information Modeling (BIM) for existing buildings-Literature review and future needs" Volk R., Stengel J., and Schultmann F. were considered to have the highest number of citations (i.e., 1253), compared with all retrieved documents, where it was published in 2014.

Table 11. Author/s with the highest number of documents/citations.

Author/s	Documents	Citations	Average Publication Year
Yang X.; Ergan S.	4	59	2015
Kučera A.; Pitner T.	4	36	2016
Ismail A.-A.	4	35	2018
Gao X.; Pishdad-Bozorgi P.	3	181	2019
Liu R.; Issa R.R.A.	3	152	2014
Wei Y.; Akinci B.	3	39	2019
Au-Yong C.P.; Ali A.S.; Ahmad F.	3	27	2015
Tang S.; Shelden D.R.; Eastman C.M.; Pishdad-Bozorgi P.; Gao X.	2	350	2020
Kang T.W.; Hong C.H.	2	206	2015
Du J.; Zou Z.; Shi Y.; Zhao D.	2	193	2018
Jazizadeh F.; Ghahramani A.; Becerik-Gerber B.; Kichkaylo T.; Orosz M.	2	150	2014
Volk R.; Stengel J.; Schultmann F.	1	1253	2014
Becerik-Gerber, B., Jazizadeh, F., Li, N., Calis, G.	1	593	2012
Xiong X.; Adan A.; Akinci B.; Huber D.	1	469	2013
Minoli D.; Sohraby K.; Occhiogrosso B.	1	457	2017

Figure 4 presents a co-authorship map and network related to the contribution of different countries in the technological research of facilities management. The map was built to reflect the number of documents each country was part of. On the other hand, Table 12 displays the number of documents, citations, average publication year, and links for the highest 20 countries, which were generated from the network. Thus, it is seen that the largest three nodes (i.e., most contributing countries) belong to the United States, China, and the United Kingdom. However, with 1483 and 1429 documents, the United States and China, respectively, have worked on documents more than double their nearest country (i.e., United Kingdom), which implies that they dominate this research field by far numbers. In addition, the United States and China had the strongest link in the network connecting them, meaning that they cooperate together more often than working with other countries. Nevertheless, even though it was noticed that the United States' citations number is almost double the number of China, when it comes to the average publication year, China has recently been more active than any other country. For the remaining countries, their numbers of documents differ closely, but they show a high variation in the citation numbers. One example is Australia, which ranks number eight on the list based on document numbers, yet has a high value of citations (i.e., 4509), coming right after the United Kingdom in fourth place.

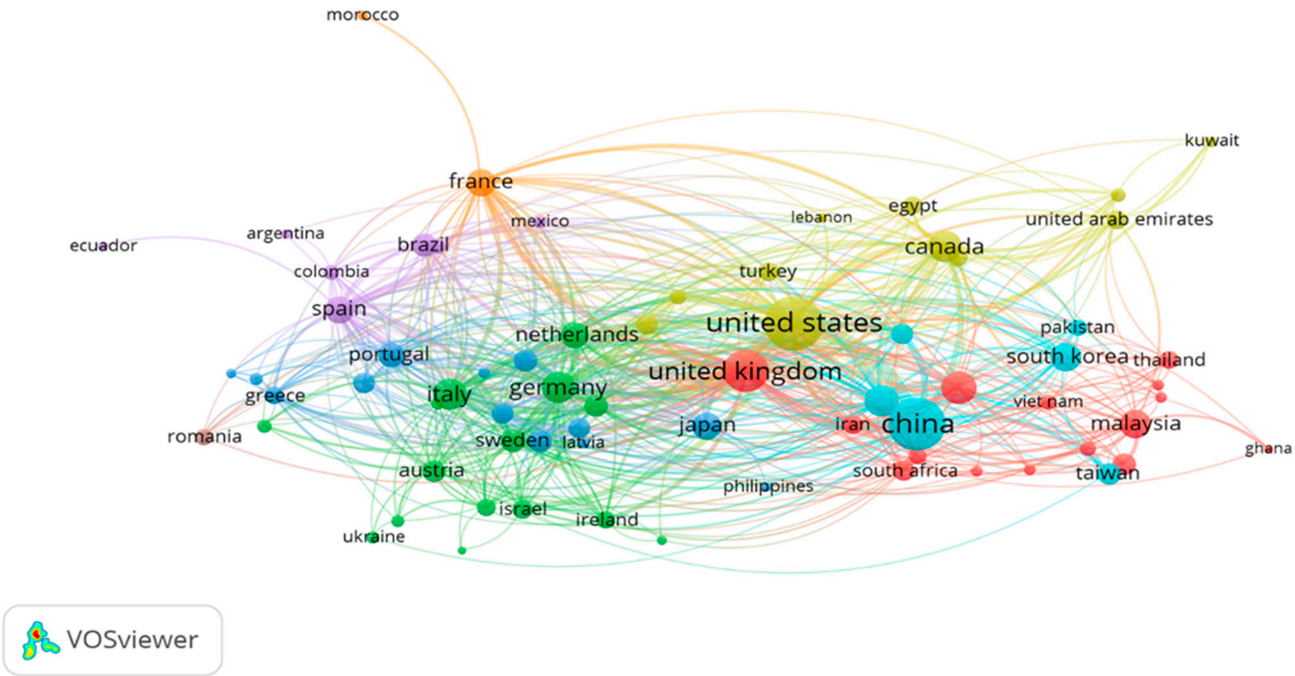

Figure 4. Countries' co-authorship network map.

Table 12. Countries with the highest number of documents/citations.

Country	Documents	Citations	Average Publication Year	Links
United States	1483	17806	2017	55
China	1429	9093	2019	39
United Kingdom	682	7416	2017	49
India	300	1681	2018	28
Germany	289	3650	2017	39
Canada	283	3842	2017	35
Italy	277	3015	2018	36
Australia	273	4509	2017	44
South Korea	200	2590	2017	20
Malaysia	198	996	2017	21
Spain	184	2188	2018	40
Japan	182	951	2016	30
France	169	1510	2017	38
Netherlands	160	976	2017	31
Portugal	120	644	2018	25
Brazil	106	465	2018	16
Sweden	101	1146	2018	34

Table 12. *Cont.*

Country	Documents	Citations	Average Publication Year	Links
Poland	93	686	2017	17
Switzerland	93	615	2017	24
Denmark	92	867	2018	31

3.5. Outlet Analysis

Based on the retrieved dataset, Table 13 displays the source titles and the number of documents published by the ten most relevant sources. In addition, Figure 5 presents the number of publications per year for the top five sources. As shown in the table and figure, the *Automation in Construction* journal ranks number one for having the greatest number of documents published since 2012, with a total of 155 publications. Moreover, it was noticed that the journal had a large increase in publications after 2017, reaching double the numbers of the years before. Furthermore, for the second most relevant source, *ACM* with their *International Conference Proceeding Series* (*ICPS*) had a very close number to the first journal with 149 documents, where their number of documents sparked after 2017, reaching 57 publications in the year 2021 alone. Thus, this emphasizes the expanded attention in the technological field of facilities and asset management in recent years. *Procedia Engineering*, with 113 documents since 2012, ranked as the third most relevant source on the list. This journal had 54 documents published in 2017, which is one of the highest numbers per year, as shown in Figure 5. However, this journal had no publications retrieved after 2017, as its latest issue was in 2018. *Advances in Intelligent Systems and Computing* is another source that showed an increase in the number of publications lately, where its numbers increased from 8 documents in 2016 to 32 in 2020. Thus, this journal, with 107 documents since 2012, ranked number four in the table. For the last journal presented in the figure, *Energy And Buildings* is the only source among the five that did not display any significant change throughout the years, as its numbers kept fluctuating without a steady trend. Nevertheless, this journal held a fifth place on the list with a total of 92 documents.

Table 13. Top source titles with the highest number of publications.

Number	Source Title	Number of Documents
1	*Automation in Construction*	155
2	*ACM International Conference Proceeding Series*	149
3	*Procedia Engineering*	113
4	*Advances in Intelligent Systems and Computing*	107
5	*Energy And Buildings*	92
6	*Advanced Materials Research*	92
7	*Buildings*	76
8	*Lecture Notes In Civil Engineering*	71
9	*Journal Of Building Engineering*	58
10	*Journal of Performance of Constructed Facilities*	54

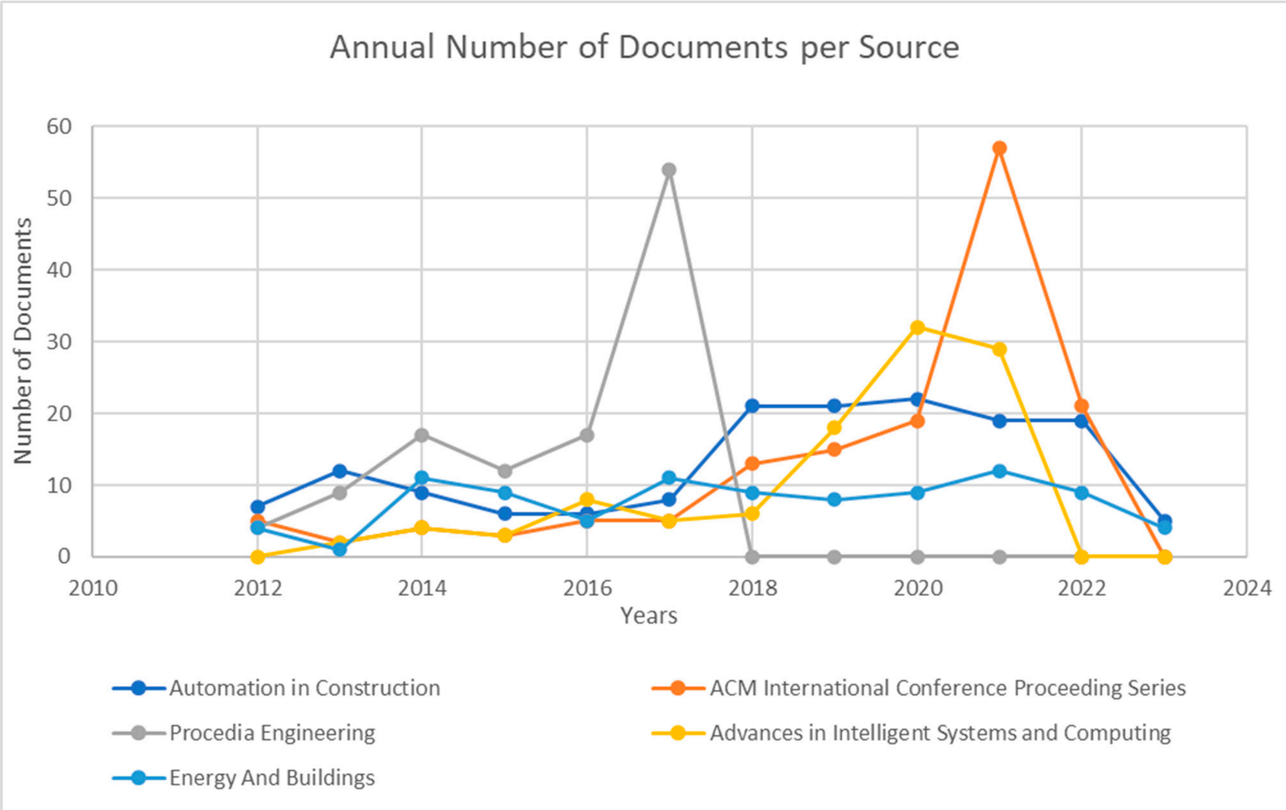

Figure 5. Annual number of publications for the top five sources.

3.6. Institutions Analysis

Table 14 shows the details of twelve affiliations that achieved the highest number of published documents based on the collected data. The institutions in the table are ranked from 1 to 12, depending on their contributions. Ranking number one, Politecnico di Milano University had the greatest number of publications with 74 documents, while being the only institution from Italy presented in the table. On the other hand, it was noticed that four out of the twelve universities were from the United States. Thus, with a total contribution of 62 documents, Georgia Institute of Technology had the highest number of documents among the United States universities and the second highest among all institutions in the table, followed by the University of California with 53 documents. Moreover, China, having three universities on the list, including Tsinghua University (47 documents), Hong Kong Polytechnic University (38 documents), and Shanghai Jiao Tong University (30 documents), held the fourth, ninth, and twelfth places, respectively. Consequently, finding seven universities in the table just from China and the United States reflects the fact that both countries are dominating this field of research. The remaining institutions in the table were all from different countries, including the University of Cambridge ranking number five with 45 documents, Universiti Teknologi Malaysia with 42 documents, ranking number six, Delft University of Technology ranking number seven with 40 documents, and Curtin University ranking number eleven with 31 documents.

Table 14. Top affiliations with the highest number of publications.

Number	Affiliations	Number of Documents	Country
1	Politecnico di Milano	74	Italy
2	Georgia Institute of Technology	62	United States
3	University of California	53	United States

Table 14. *Cont.*

Number	Affiliations	Number of Documents	Country
4	Tsinghua University	47	China
5	University of Cambridge	45	United Kingdom
6	Universiti Teknologi Malaysia	42	Malaysia
7	Delft University of Technology	40	Netherlands
8	Carnegie Mellon University	39	United States
9	Hong Kong Polytechnic University	38	China
10	Purdue University	34	United States
11	Curtin University	31	Australia
12	Shanghai Jiao Tong University	30	China

4. Discussion

4.1. Author Keywords and Smart Technology Trends

The clusters and the network of author keywords in bibliometric analysis categorized the technologies and other related keywords based on how often they were mentioned together, thus demonstrating the research trends and focus. As a result, eight clusters were generated. From these clusters, BIM, IoT, and DT technologies had the highest research interest, followed by artificial intelligence, AR, VR, and GIS. In addition, it was noticed that BIM technology has been the most attractive research topic in facilities management. The BIM keyword had the highest number of links, the closest distance to the facilities management keyword, and connections with almost all technologies mentioned, demonstrating its integration capabilities and the research dependency on its advantages. Thus, this corresponds to the results of [8,13] in terms of BIM being the most attractive research topic in facilities management in recent years and the importance of the newly emerged technologies. BIM's significance comes from the fact that maintaining and operating a structure highly depends on precise and reliable data, which can be found in the integration of BIM and facilities management systems if implemented properly [5,7,27]. Consequently, the benefits of adopting BIM in facilities management are reflected in the number of research efforts assigned to improve its capabilities. However, due to interoperability being a significant challenge, the variety of software applications, and the high initial cost of BIM, academics, and practitioners remain divided on the successful and practical information exchange process between BIM and facilities management systems [5,27,45,46].

Furthermore, IoT and DT are two other technologies that showed research significance by having the second and the third highest number of occurrences after BIM. Both technologies relate together, as IoT represents an essential part that supports DT functions. Their implementation provides real-time sensing and risk predictions for the assets, which supports the concept of smart buildings. Consequently, this advances the performance of building management by linking tangible objects with digital entities to help in asset tracking, problem visualization, and decision-making [16]. Thus, the advantages offered by IoT and DT explain their significance in current research trends. Moreover, with the current research focus in facilities management being dependent on the machine learning branch and the field of supervised learning, these technologies can have the potential to automate decision-making by combining both data collection and data science to generate accurate solutions. However, with the complexity of maintenance decisions and the number of objectives that need to be considered while making these decisions, full automation of decision-making is not there yet, as human control over the final decision is still a factor for most of the relevant studies [11]. In addition, despite the fact that some BIM and IoT integration studies are highly extensive and provide solutions that have been proven in real-world applications, the majority of studies are still in the conceptual stage [7]. Additionally, the challenge of Interoperability between different technologies' systems impose difficulties due to the big data transfer and the mapping of data schemas, especially for BIM and IoT technologies [43]. Nevertheless, the average publication years for these technologies (i.e., 2019 for IoT, 2020 for AI, and 2021 for DT) imply that researchers are still working to fill the current gaps and improve implementation processes.

Other interesting technologies that were present in the research clusters are AR and VR. They provide the opportunity to integrate with different technologies and provide visualization of different types of real information to facility management staff, thus offering several benefits to facility managers, such as participating in design decisions for long-term planning, safety simulations, process monitoring, and space management [11,21]. Moreover, it was noticed that these innovative technologies have a close relationship with one or more of the smart technologies, particularly with BIM. However, both technologies ranked among the lowest technologies in the network in terms of occurrence numbers. Additionally, despite having connections with other technologies in the network, one of AR/VR's main challenges is the lack of integration with facilities management systems [47]. Thus, this implies that researchers have been focusing more on other topics without giving much attention to these technologies' implementations. As a result, there has been a shortage of studies on their applications in facilities management [2].

On the other hand, one technology that has been gaining wide interest lately, with an average publication year of 2021, is blockchain technology. It was categorized in the same cluster as BIM, indicating that its current research trend is mainly focused on BIM applications, which can help overcome some of the challenges related to data storage, transfer, and sharing [30]. This relationship between BIM and blockchain was also highlighted in the research of [22,28], as most of the current attention concentrates on BIM–Blockchain integration. Nevertheless, with the advantages offered by blockchain, researchers started studying the possibility of integrating it with other technologies such as DT, IoT, and AI, and thus having IoT serve as the digital twin's data source, while blockchain provides safe and dependable data access, transactions, and storage [22,28]. In addition, other areas such as supply chain, smart contracts, and information management are possible applications for this emerging technology. However, since blockchain is a new technology to be employed in the construction sector, it will require further case studies and practical applications to investigate its effectiveness and potential advantages.

Lastly, other keywords such as "risk management", "information management", "big data", and "interoperability" appeared in the cluster analysis. These keywords reflect the efforts towards improving the process of making the best use of information in decision making, and the interoperability issues between facilities management systems and the technologies that are seeking integration. This describes the current research trends on information optimization.

4.2. Research Landscape and Corresponding Results

In the second part of the bibliometric analysis, some results were found to match and correspond to each other in terms of their findings, such as the results of the citation analysis and the findings of the author keyword analysis. Knowing that citation analysis identified the details of the first ten publications with the highest number of citations from the retrieved documents, another indication of the reliance of facilities management research on BIM was noticed as seven out of the ten most cited documents were related to BIM research. In addition, the three most-cited publications on the list were all part of BIM, which proves that it has been the most attractive research topic in facilities management in recent years. This corresponds to the fact presented by [25], which indicates that the attention received by BIM's publications is nearly double the average of the attention received by other articles in the field of asset management. Moreover, the fourth most-cited publication after BIM documents evaluated IoT technology. Consequently, this reflected the fact that IoT is the second most-occurring cluster after BIM.

In other related results, the findings of the countries' co-authorship and the institutions analysis were noticed to be matching in terms of the first two countries. In countries' co-authorship, the analysis evaluated the authors and countries connected with the highest number of documents/citations, which provided a conceptual image of the prime contributors to this research field. Thus, the results indicated that the United States and China are dominating the technological research of facilities management by large numbers depending on both the number of documents and citations, while their nearest country is the United Kingdom, with half their document numbers. The dominance of the United States on the research of asset management was also part of the main findings in the research of [9]. On the other hand, the institution analysis ranked the details of twelve affiliations that provided the highest number of published documents from the collected data. As a result, four and three out of the twelve universities with the most documents were found to be from the United States and China, respectively, where the total numbers of documents combined were 188 for the United States universities and 115 for China's universities, which were higher than the institution with the highest number of documents on the list (i.e., Politecnico di Milano, 74 documents). Consequently, the results correspond to the fact that the United States and China are the current major contributors to this field of research. Nevertheless, there were no institutions present from the United Kingdom in the institutions analysis even though it ranked right after the United States and China in the countries' co-authorship analysis.

4.3. Expanded Attention and Corresponding Results

The results presented expanded research interest in providing smart technological solutions for facility managers in recent years. Consequently, it was found in the journal mapping analysis that three out of five journals with the highest number of documents from the retrieved dataset displayed an increase in their number of publications after 2017. On the other hand, in the overview analysis, the number of publications per year for all publications (from the dataset) was found to have increased after 2018, which emphasizes the fact that there has been expanded attention in the technological field of facilities and asset management in recent years. Consequently, the results of journal mapping and overview analysis correspond in terms of the recently expanded attention. This increased interest in smart facilities management research is also one of the main findings in the research [8,9]. The triggers to this recent movement can be assumed to be due to the integration opportunities and the increased interest in BIM technology advantages; the various technological solutions such as IoT, DT, and AI; and the integration opportunities of new technologies such as blockchain to fill current gaps, as most of the research is concentrated on their applications.

5. Conclusions

In conclusion, facilities management represents the longest phase of an establishment's life cycle, and the highest cost producer accounting for about 85% of the life-cycle cost [1,2]. Consequently, several academics have recommended improving this sector by implementing intelligent procedures and technologies [7,48]. Thus, facilities management has been gaining popularity as an area of study in the past decades [8,9]. However, the construction sector is still argued to have a slow pace of digitization in asset management terms [7,8,13]. Additionally, with data being the most important requirement for efficient operation and maintenance, facility managers still face information and communication challenges while implementing existing systems [10,49]. As a result, managers spend significant time and effort gathering information from various combinations of digital information and hard-copy documents [45]. Indeed, there is a need to stay on top of new innovations and gain a deeper understanding of the current state of research in the field of smart and digital facilities management [7,8,25]. Consequently, the research efforts and the trends of smart technologies implemented in facilities management after 2012 were analyzed to gain a deeper understanding of the current state-of-the-art research in this field. In addition, the research identified the most influential authors, countries, sources, and research topics, as well as research gaps and areas for future exploration. The Scopus database was utilized as the main source of information for the literature search, where a total of 7236 publications were gathered for analysis. Moreover, VOSviewer version 1.6.18. were used as the analysis software for the quantitative trend analysis.

5.1. Concluding Remarks and Areas for Future Exploration

The co-occurrence analysis of author keyword identified several findings and potential areas for future research. Given that the current research trend is mainly focused on BIM technology, followed by IoT and DT, the actual implementation of these technologies in facilities management still faces many challenges, such as the high initial cost and their integration of a variety of software applications. For this reason, it suggests the need to provide more cost-effective and practical solutions and being applied in real-world case studies. In addition, interoperability is one of the main challenges for applying smart technologies such as BIM, IoT, and DT. Our results revealed that it only had 33 occurrences compared with more than 400 for BIM, indicating that researchers need to give more attention in this issue. Consequently, this information opens a vital area for future research on interoperability. Moreover, AI, a technology that highly connects to all other technologies mentioned, provides a great solution to automate facility management decision-making by combining data collection and data science to generate accurate solutions. Consequently, with an average publication year of 2020, researchers still have an opportunity to overcome challenges related to the complexity of maintenance decisions and achieve full automation of the decision process. AR and VR represent other technologies that can display and provide important information to help improve facility managers' operations. However, compared with other technologies, both technologies have two of the lowest occurrences. It implies that they lack integration with facilities management systems due to the shortage of studies on their applications. Thus, with the advantages offered by these two technologies, more focus should be given to AR and VR integrations. Lastly, another important area for future exploration is blockchain technology. The reviewed literature mentioned the benefits and advantages of adopting this new technology in facility management. However, current blockchain research is mostly focused on BIM applications only. Hence, researchers still have a wide range of opportunities to evaluate the integration of this technology with other technologies, such as IoT and DT, and in other areas of application, such as supply chains, smart contracts, and information management.

The findings of the remaining analyses helped draw the current research landscape in the field of smart facilities management. The main results of these analyses are summarized as follows:

(1) Growth in the research interest in providing smart technological solutions for facilities management is noticed in recent years.
(2) Seven out of the ten most-cited documents in this field are related to BIM research.
(3) The United States and China are noticed to be the major contributors (documents and citations) in this research field.
(4) Politecnico di Milano University from Italy has the highest number of publications related to this field of study, followed by Georgia Institute of Technology and the University of California from the United States.
(5) Seven out of the twelve universities with the greatest number of related publications are from the United States and China.
(6) Automation in Construction and ACM ICPS journals rank as the highest two journals in terms of publication numbers for this area of research.

5.2. Limitations and Recommendations

With the presented results, facility management is still facing some technological challenges, where the road toward optimization and full automation in decision-making is still in progress. Various smart technological solutions have been gaining research interest lately with many integration possibilities. Thus, the findings of this research should be able to guide researchers in discovering the connections between smart technologies, understanding the current research gaps and the areas for future exploration, as well as assisting them in making informed decisions about which smart technologies and trends to focus on. However, the research included some limitations that should be underlined, including the use of one search engine (i.e., Scopus) for data collection. Thus, future studies can include more engines, such as Web of Science, for additional resources. In addition, the strings of keywords employed in the search and the filtering processes might have excluded some of the related literature due to the large number of publications identified. As a result, future research should evaluate each technology's applications through a systematic review and case studies to analyze its benefits and integration capabilities in facilities management. In addition, researchers should assess the return and advantages of these technologies to facility managers compared with their current challenges and implementation efforts. Moreover, future research could focus on the possible areas of application for new innovative technologies, such as blockchain, and provide case studies of their benefits to facilities management.

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