applied sciences

MDPI

Review

Building Information Modelling and Internet of Things Integration for Facility Management—Literature Review and Future Needs

Antonino Mannino *, Mario Claudio Dejaco and Fulvio Re Cecconi

Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio 31, 20133 Milano, Italy; mario.dejaco@polimi.it (M.C.D.); fulvio.rececconi@polimi.it (F.R.C.)
* Correspondence: antonino.mannino@polimi.it

Abstract: Digitisation of the built environment is seen as a significant factor for innovation in the Architecture, Engineering, Construction and Operation sector. However, lack of data and information in as-built digital models considerably limits the potential of Building Information Modelling in Facility Management. Therefore, optimisation of data collection and management is needed, all the more so now that Industry 4.0 has widened the use of sensors into buildings and infrastructures. A literature review on the two main pillars of digitalisation in construction, Building Information Modelling and Internet of Things, is presented, along with a bibliographic analysis of two citations and abstracts databases focusing on the operations stage. The bibliographic research has been carried out using Web of Science and Scopus databases. The article is aimed at providing a detailed analysis of BIM–IoT integration for Facility Management (FM) process improvements. Issues, opportunities and areas where further research efforts are required are outlined. Finally, four key areas of further research development in FM management have been proposed, focusing on optimising data collection and management.

Keywords: Building Information Modelling (BIM); Internet of Things (IoT); facility management; cyber-physical systems; digital twin

Citation: Mannino, A.; Dejaco, M.C.; Re Cecconi, F. Building Information Modelling and Internet of Things Integration for Facility Management—Literature Review and Future Needs. *Appl. Sci.* **2021**, *11*, 3062. https://doi.org/10.3390/app11073062

Academic Editor: Jürgen Reichardt

Received: 27 February 2021
Accepted: 25 March 2021
Published: 30 March 2021

1. Introduction

The construction industry has a relatively low digitisation level compared to other sectors [1,2]. Although it is seen as a major factor in the innovation of the Architecture, Engineering and Construction and Operations (AECO) sector, digitisation in the construction industry still shows a slow growth rate [3]. However, improvements in methodologies and technologies are under development to better manage AECO processes [4].

This article presents a literature review on the integration of Building Information Modelling (BIM) and Internet of Things (IoT) for the Facility Management (FM) of the constructed asset. It is divided into four main parts: (a) an overview of FM and the impact of digitisation in the sector; (b) the description of the research method; (c) an in-depth content analysis of 99 selected journals' articles on BIM-IOT integration for FM, which allows identifying both benefits/opportunities and issues/limits at technical and operational levels; (d) conclusions and a description of a possible future research agenda.

The context is the fourth industrial revolution (Industry 4.0), where several technological changes in many sectors have been made, including in the AECO one [5,6].

There are many studies on the application of digital technologies aiming to promote digitisation in the built environment. However, compared to the design and construction stages, there is a lack of research on applying these new technologies in the operation and use stage of the building life cycle [7], particularly for the FM sector. FM represents up to 85% of the whole life cycle cost of the building [8]. Even though the life cycle cost of a building can and should be controlled in the design phase the adoption of innovative tools and technologies to improve FM in existing buildings is continually increasing. Wong et al. [7] identified and discussed several possibilities for future research into digital technologies like integrating FM with BIM, reality capture technology, IoT, Radio Frequency Identification (RFID), and Geographic Information System.

Among several studies on applying new technologies, a significant solution taken into consideration in the last years by the AECO sector has emerged: the Cyber-Physical Systems (CPS) [6]. CPS, also known as Digital Twins (DT), are systems based on the combination of physical and digital objects. Through simulation of an as-built component (or system), using digital models and several types of data, DT allows mirroring the life of its corresponding real twin to forecast the health of building components, their service life, faults [9] and, in general, the building performances [10].

Even if not risk-free, these digital innovations will enable new dynamics and allow new services that will improve efficiency and sustainability in building management processes [11].

1.1. Facility Management

Facility management is a multidisciplinary topic that requires the collaboration and coordination of different people [6]. ISO 41011:2017 defines FM as an "organisational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business" [12].

According to International Facility Management Association (IFMA), there are 11 core competencies in FM [13]: Occupancy and Human Factors, Operations and Maintenance (O&M), Sustainability, Facility Information and Technology Management, Risk Management, Communication, Performance and Quality, Leadership and Strategy, Real Estate, Project Management, Finance and Business.

Currently, not all buildings have optimal management [14,15] due to outdated procedures that cause a lack of data and information. In other cases, despite the use of sensors/automatic devices and databases, the information collected is not entirely exploited [16]. An example is given by FM information systems, e.g., Computerised Maintenance Management Systems (CMMS), Energy Management Systems (EMS) and Building Automation Systems (BAS), where data are often fragmented and manually entered after the handover of the building. Fragmentation and data poorness could generate laborious and inefficient processes [7]. Furthermore, FM operators often rely on paper documents in their daily activities. This increases both the time needed and the difficulties of getting accurate information [17]. For these reasons, the improvement of both FM tools and processes is a crucial issue in FM companies [18]. Hence, with increasing industry interest, a review of the current status and a description of a future research agenda on FM is needed.

1.2. Digitisation and FM

New technologies have transformed many people's daily lives and have revolutionised several traditional industry practices aiming to achieve efficiency, accuracy, and precision. This evolution has gained momentum due to advancements in technologies such as the Internet of Things (IoT), big data, cloud computing and cyber-physical systems [19].

The strengths of these innovations 4.0 lie in monitoring, controlling, interoperability, real-time information processing and process self-optimisation [19]. The physical world's connection with the virtual world enables products and components to create a self-adapting and self-managing communication network [20].

In the construction sector, the first attempt at digitisation aiming to increase the sector's efficiency has already been seen with the spread of BIM [21].

1.3. Building Information Modelling for FM

The United States National Institute of Building Sciences (NIBS) defines BIM as "The digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards” [22].

In recent years, BIM has been more and more employed in the AECO sector to improve information management. BIM Models (BIMs) allow integrated management of information throughout the building’s entire life cycle, hence improving FM [23]. On the one hand, BIM allows working more efficiently during the design and construction phases by developing a 3D model that avoids project interference and allows project time and cost calculation. On the other hand, it allows acquiring data created during several phases of the building life cycle to use them in operations management, maintenance activities, environmental analysis and energy performance simulations. The latter is related to Building Energy Modelling (BEM), which has become an essential aspect for FM.

Benefits of using BIM in FM include providing “as-is” information and enabling Facility Managers to work on information using a single source of data, overcoming all the issues deriving from the sources’ fragmentation.

A BIM model has different Levels of Information Needs [24]. To deal with them, the American BIMForum defined the Level of Development (LOD) Specification. This reference enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process. A BIM model has six Levels Of Development (LOD): LOD 100, LOD 200, LOD 300, LOD 350, LOD 400 and LOD 500 [25]. Each LOD defines how much information is included in a building component. The higher the LOD, the greater the clarity and reliability of data and information.

According to Love et al. [26], using the highest LOD is possible in order to enrich the digital model with all the information necessary for assets management and maintenance. In this way, data are more efficiently stored in a single file without fragmentation or loss of information. Moreover, improving the handover process is possible using fewer paper documents or manual transfer of information [26].

As early as 2012, Becerik-Gerber et al. [27] have defined, also through surveys and interviews, how BIM can support FM practices. Their paper assesses the status of BIM implementations in FM, potential applications, level of interest in BIM utilisation, application areas, and data requirements for BIM-enabled FM practices. To date, studies on BIM application in FM confirm momentum (e.g., [18,28–33]).

However, despite all the advantages, BIM is not often used in the FM phase. The most significant causes that hinder this integration are:

(1) Industry perception, which considers BIM models just as 3D models and not as informative models with business value [34].
(2) Lack of involvement of the facility managers in the creation of the BIM model [7,35]. Consequently, less information useful for FM is integrated into the model.
(3) The need for interoperability between BIM and FM technologies and the lack of open systems and standardised data libraries that can be utilised as a bridge between BIM and CAFM technologies [36].
(4) Lack of clear roles, responsibilities, contract and liability framework [36].
(5) Furthermore, the main limitation of BIM methodology is its static information: data are provided during the design phase but not updated during the building’s life cycle [37]. This is a relevant issue for buildings management, and research is moving in this direction.

1.4. Internet of Things for FM

Asghari, Rahmani and Javadi [38] define IoT as “an ecosystem that contains smart objects equipped with sensors, networking and processing technologies integrating and working together to provide an environment in which smart services are taken to the end-users”. They show how this ecosystem is being applied in healthcare, environmental, smart cities, commercial and industrial contexts. IoT has led to an interconnection between people and objects at an unprecedented scale and pace [39] and will allow new strategies to improve quality of life [40]. Furthermore, connected devices could be programmed to make autonomous decisions and adequately inform users to make the best decisions [41].

Operation and maintenance stages represent 50–70% of the total annual facility operating costs [42], and buildings management requires integrating and analysing different types of data and information generated by various stakeholders. This implies that improved data and information management can have a significant impact on building performance.

In this context, the application and integration of IoT and BIM technologies to gather and store data/information for the entire life cycle of the building have caught wide attention. In recent years, a growing number of innovations have been developed [7].

IoT and smart connection have great potential in optimising FM activities, including inventory and document management, building security, logistics and materials tracking, tracking of building component life cycle and building energy controls [7]. Several studies about the use of data coming from IoT devices have been carried out (e.g., [43–45]), although many of them do not include the integration of BIM.

2. Scope and Aim of the Research

As mentioned before, BIM and IoT- based data sources is a relatively new field. One can consider BIM and IoT data as two complementary entities, where one covers the lack of the other. Researchers have addressed different aspects of BIM, IoT and their use in an integrated way: sustainability, risks, safety and so forth.

In this article, integration is addressed more from the point of view of the information collected/transmitted by sensors and actuators (and used for a specific purpose) than from that of the software or platform used. Hence, studies and research published on BIM and IoT data integration are analysed in this paper. The content is structured as a bibliographic investigation through which an analysis of these technologies' current use is carried out. The aims of this research are:

(1) To provide a detailed bibliographic analysis of the research efforts on BIM–IoT integration for FM processes improvements
(2) To identify limitations in the research and introduce a roadmap for further research on FM improvements through new technologies.

3. Materials and Methods

This study analyses and categorises existing studies on BIM and IoT integration for FM according to the methodology shown in Figure 1. To review BIM-IoT integration comprehensively in the Facility Management context, two electronic databases of peer-reviewed literature have been taken into consideration: Scopus and Web of Science (WoS). The bibliometric analysis presented here aims to analyse academic publications and trends to evaluate the existing research performance and understand patterns. As the first step, keywords to select articles on BIM-IoT integration for FM functions are defined. Table 1 highlights the keywords used to find publications on BIM and IoT. Table 2 shows the set of keywords for each FM core competence.

Table 1. Keywords used for research in the two electronic databases of peer-reviewed literature Scopus and Web of Science (WoS). The asterisk "*" after the keywords tells the search engine to look for all the words beginning with that keywords, i.e., "sensor*" tells the search engine to look for the words "sensor", "sensors", "sensoring", etc ... The quotations marks surrounding two or more words tell the search engine to look for the phrase and not the words, i.e., "industry foundation classes" is use to search for the prhase and not for the words industry or foundation or classes.

Tools	Keywords
BIM	BIM or "Building Information Modelling" or "Building Information Modeling" or IFC* or "industry foundation classes"
IoT	IoT or "Internet of things" or sensor* or WSN or "Wireless Sensor* Network*" or "Real Time Data" or "Real-Time Data"

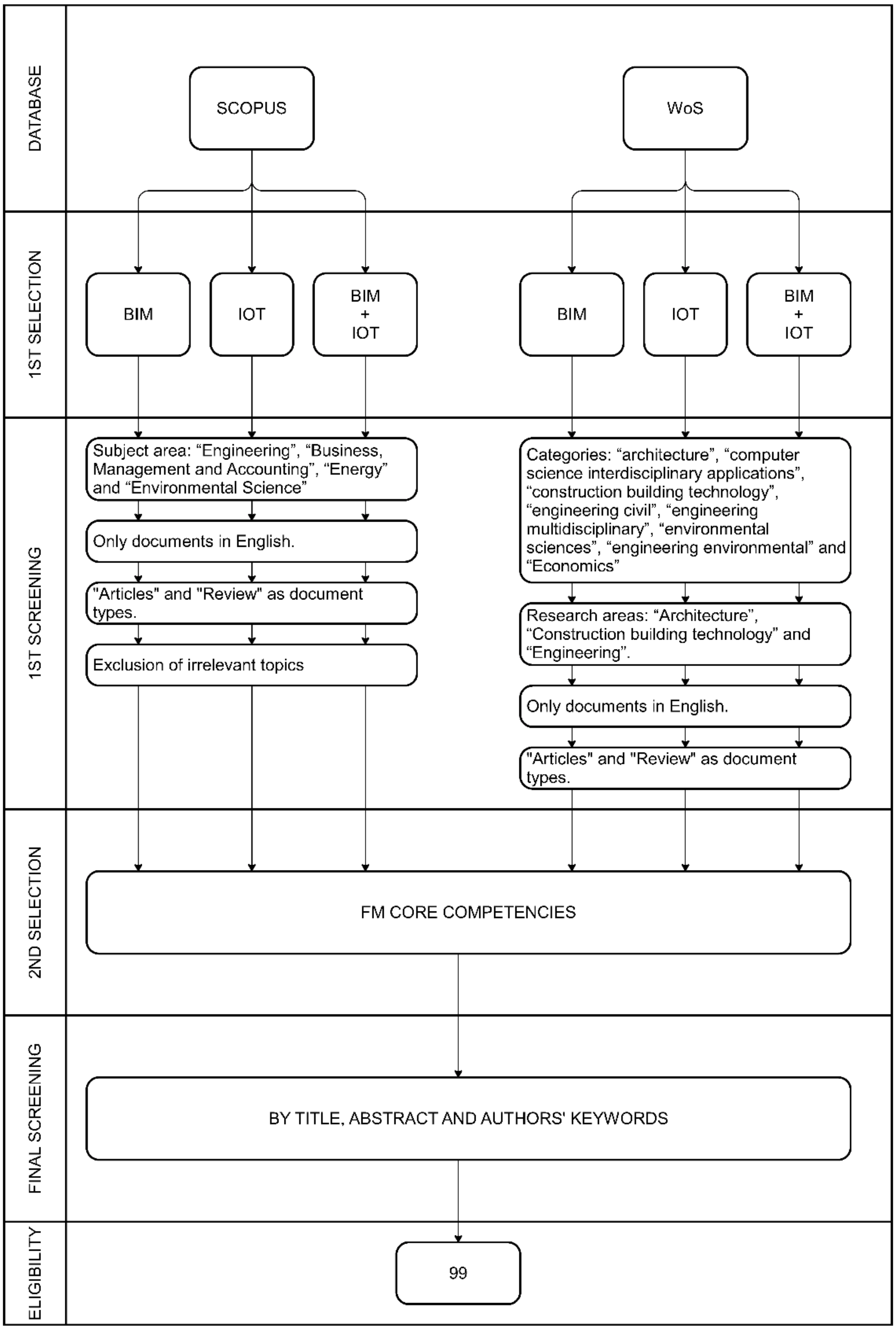

Figure 1. Research methodology.

After the keywords selection, Scopus and WoS databases were queried, using the keywords shown in Table 1, to find publications dealing with: (a) BIM; (b) IoT; and (c) BIM and IoT at the same time. This first-level query investigated how much these topics have been explored by researchers, even outside the FM field.

In a second-level query on the two databases, BIM and IoT keywords (Table 1) were coupled with FM core competencies (Table 2) to measure how deep BIM and IoT permeate FM core competencies.

Table 2. FM and its core competencies keywords used for research in the two electronic databases of peer-reviewed literature Scopus and Web of Science (WoS).

FM and Core Competencies	Keywords
Communication	Communication* or report* or "communication* strategy"
Finance and Business	"Financial management" or budget* or financial or contract* or procurement
Human Factors	Occupancy or "Workplace environment" or "Occupant services" or "Occupant health" or "Occupant safety" or "Occupant security"
Leadership & Strategy	Leadership or "team* management" or "team* organisation" or "conflict management"
O&M	FMM or "Facility Maintenance Management" or "Facilities Maintenance Management" or maintenance or "maintenance management" or operation* or "Physical safety and security" or "Work management systems"
Project Management	"project management" or "project execution" or "project monitor" or "project outcomes" or "project schedule"
Quality and Performance	"Quality management" or "key performance indicators" or KPI or "service level agreements"
Real Estate and Property Management	"real estate management" or "property management" or "Real estate strategies" or "Real estate assessment" or "Asset management"
Risk Management	"Risk*" or "Emergency*"
Sustainability	Sustainab* or "Energy*" or "Water*" or "Waste*" or BEM*
Information and Technology Management	"intelligent building systems" or "automation" or "data collection" or "Information management" or "Information security*" or "Information system" or "cyber-security"
FM	FM or "Facility Management" or "Facilities Management"

A set of filters was applied to the various searches to limit the large number of results. To perform this selection in the WoS database, results were as follows:

- Refined, considering the following WoS categories: "architecture", "computer science interdisciplinary applications", "construction building technology", "engineering civil", "engineering multidisciplinary", "environmental sciences", "engineering environmental" and "economics" (because of Finance and Business FM core function).
- Refined, considering only the following research areas: "architecture", "construction building technology" and "engineering".
- Refined, considering only documents in English.
- Refined, considering only articles and reviews as document types to acquire higher-quality documents.

Articles from "computer science interdisciplinary applications" and "engineering multidisciplinary" domains were included in the review to ensure a comprehensive review of BIM and IoT device integration. Finally, the results were further filtered (by title, abstract and author's keywords) to remove articles not relevant for the research scope.

To perform a similar selection in the Scopus database, results were as follows:

- Refined, considering the following subject area: "engineering", "business, management and accounting", "energy" and "environmental science".
- Refined, considering only documents in English.
- Refined, considering only articles and reviews as document types to acquire higher-quality documents.
- Filtered, excluding irrelevant topics (e.g., medicine, chemistry, biology).

As the last step, the two search results were combined, and duplicated articles were excluded. Finally, a list of 99 articles on the BIM-IOT integration was selected. Five out of ninety-nine articles are general reviews on BIM-IOT for FM and were already discussed in the introduction. To derive patterns and propose future research directions, qualitative data analyses of the 94 articles based on each article's technical aspect were carried out, as discussed in Section 5.

4. Results

The first result of the query using the keywords combination method explained in Section 3 shows a fairly clear gap between the number of publications on the three main topics. More than 95% of the articles deal with IoT (Table 3). A limited number of publications, less than 4%, of articles deal with BIM. Lastly, the integration of BIM and IoT is still at an early stage.

Table 3. Number of journal articles on BIM, IoT and their integration resulting from Scopus and WOS databases research (until February 2021).

	Scopus	**WoS**
BIM	3316	2717
IoT	157,108	31,088
BIM + IoT	237	166

Considering the number of publications on BIM and IoT integration in the last 30 years, it is possible to see how the first significant increase is registered after 2013 (Figure 2). Furthermore, publications grew almost simultaneously in both citation databases. Interestingly, 80% of the articles on Scopus and 85% of the articles on WoS were published during the last five years; this means that BIM-IoT integration is a new domain with increasing interest, especially during 2019 and 2020. Accordingly, the implementation of BIM-IoT integration for FM is also a new domain, with a limited number of publications (red line in Figure 2).

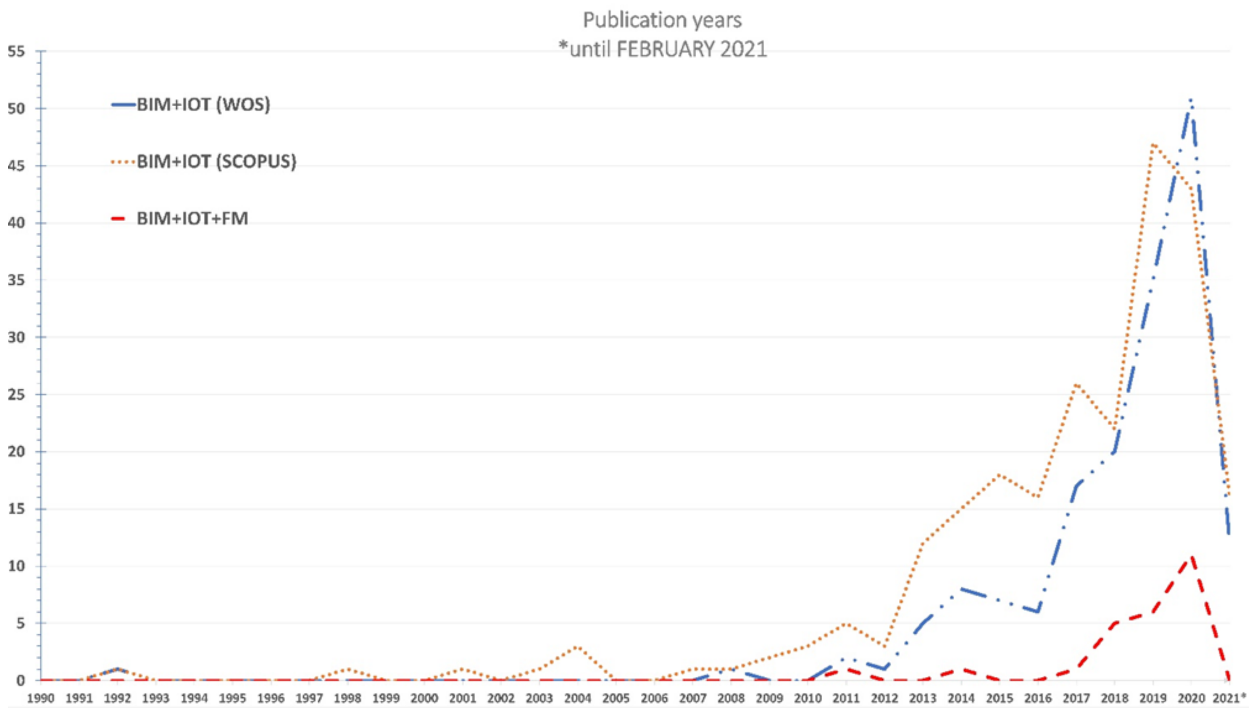

Figure 2. Number of publications per year (* until February 2021) dealing with BIM and IoT in Scopus (yellow dotted), in Web of Science (blue dash-dotted) and number of product dealing with BIM and IoT for Facility Management (red dashed).

A further query using FM core functions keywords (Table 2) was carried out to find as many articles as possible on BIM and IoT integration in the FM field. Results are shown in Table 4.

Table 4. Journals' articles on BIM, IoT and their integration for FM and its core functions from WoS (W) and Scopus (S) databases (until February 2021).

	Functions	Tools		
		BIM	**IoT**	**BIM + IoT**
FM Core Functions	Communication	426 (W) + 509 (S)	3920 (W) + 28539 (S)	42 (W) + 55 (S)
	Finance & Business	293 (W) + 468 (S)	417 (W) + 3413 (S)	8 (W) + 15 (S)
	Human Factors	31 (W) + 43 (S)	362 (W) + 974 (S)	4 (W) + 4 (S)
	Leadership and Strategy	32 (W) + 242 (S)	18 (W) + 500 (S)	1 (W) + 17 (S)
	O&M	557 (W) + 746 (S)	4374 (W) + 24709 (S)	66 (W) + 64 (S)
	Project Management	157 (W) + 965 (S)	20 (W) + 1875 (S)	6 (W) + 53 (S)
	Quality	33 (W) + 200 (S)	61 (W) + 3767 (S)	1 (W) + 2 (S)
	Property Management	57 (W) + 169 (S)	42 (W) + 1087 (S)	7 (W) + 19 (S)
	Risk Management	253 (W) + 267 (S)	1084 (W) + 5319 (S)	17 (W) + 75 (S)
	Sustainability	709 (W) + 794 (S)	7733 (W) + 33413 (S)	59(W) + 106 (S)
	Technology	370 (W) + 1875 (S)	1219 (W) + 30946 (S)	34(W) + 104 (S)
FM		237 (W) + 236 (S)	71 (W) + 341 (S)	25 (W) + 81 (S)

The query was limited to journals' articles: Table 4 shows how many products were found in each database matching each FM core function with the three tools' categories.

Although the contemporary use of BIM and IoT is relatively recent, some FM core functions like "Sustainability", "O&M", "Communication", and "Technology" have a significant number of publications. On the contrary, perhaps because of the novelty of the two tools' simultaneous use, some functions have a minimal number of publications. Noteworthy, "Sustainability" is the most studied core function even when considering BIM or IoT separately. The number of publications in the several FM core functions is relatively homogeneous if only BIM products are queried.

To narrow down the scope of the review, further analysis was done on the title and abstract of each of the 904 articles dealing with BIM and IoT, discarding articles not directly related to the construction sector and FM (Table 5).

Eventually, duplicates, i.e., articles covering more than one core function or present in both databases, were discarded, and the final list of 99 articles emerged. On these 99 articles published between 2013 and 2021 (Table 6), a bibliometric analysis was carried out using the R package Bibliometrix [46].

Over the period under review, and based on the proposed selection criteria, most of the articles on BIM-IoT integration for FM were published in *Automation in Construction*, with 27 of the total selected articles. Followed by: *Applied Sciences* (6), *Journal of Computing in Civil Engineering* (5), *Sustainability* (5), *Advanced Engineering Informatics* (3), *Building and Environment* (3), *Journal of Construction Engineering and Management* (3) and *Journal of Information Technology in Construction* (3). The remaining journals' publication rates varied between one to two articles during the considered period.

The bibliometric analysis also reveals that a significant number of publications have been conducted in the USA, with 18 publications, followed by China (12), Australia (9), Hong Kong (8), UK (7), Canada (7), Germany (6) and Italy (6). The remaining countries had less than six articles published during the considered period. Furthermore, the top 10 most cited papers are summarised in Table 7.

Table 5. Journals' articles on BIM–IoT integration, for each FM core competence, from Web of Science and Scopus databases.

FM Core Competencies	BIM + IoT Selected Articles	
	Web of Science	Scopus
Communication	20	24
Finance and Business	3	6
Human Factors	5	4
Leadership & Strategy	0	4
O&M	28	28
Project Management	2	14
Quality	0	0
Real Estate and Property Management	4	5
Risk Management	10	23
Sustainability	28	43
Information and Technology Management	9	42
Facility Management	14	37
Total	**68**	**75**

Table 6. Annual publications of journal articles on BIM–IoT integration for FM (* until February 2021).

Year	Articles
2013	5
2014	9
2015	4
2016	4
2017	12
2018	14
2019	19
2020	24
2021 *	8

Table 7. Top 10 of the most cited articles sorted by the number of global citations (until February 2021).

Title	Authors	Year	Source	doi	Cit
A conceptual framework for integrating building information modeling with augmented reality. (IT)	Wang, X.; Love, P.E.D.; Kim, Mi Jeong et al.	2013	Automation in Construction	10.1016/j.autcon.2012.10.012	117
Prefabricated construction enabled by the Internet of Things. (PM)	Zhong, R.Y., Peng, Y., Xue, F. et al.	2017	Automation in Construction	10.1016/j.autcon.2017.01.006	110
A BIM centered indoor localisation algorithm to support building fire emergency response operations (R)	Li, N., Becerik-Gerber, B., Krishnamachari, B., Soibelman, L.	2014	Automation in Construction	10.1016/j.autcon.2014.02.019	106
Case Study of BIM and Cloud-Enabled Real-Time RFID Indoor Localization for Construction Management Applications (PM)	Fang, Y., Cho, Y.K., Zhang, S., Perez, E.	2016	Journal of Construction Engineering and Management	10.1061/(ASCE)CO.1943-7862.0001125	91
Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors	Park, J., Kim, K., Cho, Y.K.	2017	Journal of Construction Engineering and Management	10.1061/(ASCE)CO.1943-7862.0001223	91
CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined spaces	Riaz, Z., Arslan, M., Kiani, A.K., Azhar, S.	2014	Automation in Construction	10.1016/j.autcon.2014.05.010	85

Table 7. *Cont.*

Title	Authors	Year	Source	doi	Cit
An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction	Li, C.Z., Xue, F., Li, X., Hong, J., Shen, G.Q.	2018	Automation in Construction	10.1016/j.autcon.2018.01.001	84
Monitoring thermal comfort in subways using building information modeling	Marzouk, M., Abdelaty, A.	2014	Energy and Buildings	10.1016/j.enbuild.2014.08.006	61
A framework for integrating BIM and IoT through open standards	Dave Bhargav, Andrea Buda, Antti Nurminen, Kary Framling	2018	Automation in Construction	10.1016/j.autcon.2018.07.022	60
A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends	Tang, S., Shelden, D.R., Eastman, C.M., Pishdad-Bozorgi, P., Gao, X.	2019	Automation in Construction	10.1016/j.autcon.2019.01.020	59

Although the most cited article overall is the one written by Wang in 2013, the articles with the highest number of citations per year are those of Tang et al. (2019) with 29.5 Citations Per Year (CPY) and Li et al. (2018) with 28 CPY. Other articles most cited per year are Zhong et al. (2017) (27.5 CPY), Park et al. (2017) (22.8 CPY), Dave Bhargav et al. (2018) (20 CPY). It emerges that if we exclude the first, which is a general review on BIM-IoT integration, the most cited articles mainly concern project management and risk management. In Table 8, each article is assigned to a single core function according to the title and abstract analysis made by authors. Accordingly, an FM core competencies content analysis to generate patterns and trends of existing research has been done.

Table 8. Selected articles assignment to a single FM core function according to the title and abstract analysis made by the authors.

FM Core Competencies	References
Finance and Business	Chong et al. (2020) [47]
Human Factors	Marzouk et al. (2014, 2014) [48,49], Natephra et al. (2017) [50], Zhong et al. (2018) [51], Ma et al. (2019) [52], Lin et al. (2020) [53], Zaballos et al. (2020) [54]
Leadership and Strategy	Niu et al. (2016) [55], Chang et al. (2018) [56]
O&M	Rio et al. (2013) [57], Zhang et al. (2015) [58], Delgado et al. (2017) [59], Jeong et al. (2017) [60], Delgado et al. (2018) [61], Boddupalli et al. (2019) [62], Fitz et al. (2019) [63], Mannino et al. (2019) [64], Valinejadshoubi et al. (2019) [65], Cheng JCP et al. (2020) [66], Kameli et al. (2020) [67], Ma et al. (2020) [68], Moretti et al. (2020) [69], O'Shea and Murphy (2020) [70], Xie et al. (2020) [71], Yin et al. (2020) [72]
Project Management	Costin et al. (2015) [73], Fang et al. (2016) [74], Park et al. (2017) [75], Zhong et al. (2017) [76], Chen et al. (2018) [77], Li et al. (2018) [78], Tagliabue et al. (2018) [79], Hamooni et al. (2020) [80], Pan and Zhang (2021) [81]
Quality and Performance	Hernández et al. (2018) [82], Martinez et al. (2019) [83]
Real Estate and Property Management	Atazadeh et al. (2019) [84], Moretti et al. (2020) [85]
Risk Management	Shiau et al. (2013) [86], Arslan et al. (2014) [87], Li et al. (2014) [88], Riaz et al. (2014) [89], Cheng MY (2017) [90], Park and Hong (2017) [91], Park et al. (2017) [92], Riaz et al. (2017) [93], Beata et al. (2018) [94], Chou et al. (2019) [95], Parn et al. (2019) [96], Yu et al. (2019) [97], Asadzadeh et al. (2020) [98], Cheng JCP et al. (2020) [99], Lei et al. (2020) [100], Lin et al. (2021) [101], Tian et al. (2021) [102]

Table 8. *Cont.*

FM Core Competencies	References
Sustainability	Gökçe et al. (2013) [103], Osello et al. (2013) [104], Cheng et al. (2014) [105], Gökçe et al. (2014) [106], Gökçe et al. (2014) [107], Kensek (2014) [108], Ness et al. (2015) [109], Zhao et al. (2015) [110], Habibi (2016) [111], Lee et al. (2016) [112], Habibi (2017) [113], McGlinn et al. (2017) [114], Dave et al. (2018) [115], Francisco et al. (2018) [116], Pasini (2018) [117], Ma et al. (2019) [52], Kang (2020) [118], Mataloto et al. (2020) [119], Hirakraj et al. (2021) [120], Sepasgozar et al. (2021) [121], Tagliabue et al. (2021) [122]
Information and Technology Management	Wang et al. (2013) [123], Alves et al. (2017) [124], Edmondson et al. (2018) [125], Kang et al. (2018) [126], El Ammari et al. (2019) [127], Kazado et al. (2019) [128], Rashid et al. (2019) [129], Rogage et al. (2019) [130], Saar et al. (2019) [131], Tsai et al. (2019) [132], Zhai et al. (2019) [133], Edirisinghe et al. (2020) [134], Pavòn et al. (2020) [135], Quinn et al. (2020) [136], Valinejadshoubi et al. (2020) [137], Zhang et al. (2020) [138], Gao et al. (2021) [139]
Reviews	Wong et al. (2018) [7], Stefanic et al. (2019) [140], Tang et al. (2019) [141], Boje et al. (2020) [142], Panteli et al. (2020) [143], Hou et al. (2021) [144]

5. Discussion

The bibliometric analyses described in this paper identified the main characteristics of the literature in BIM, IoT and the integration of the two aiming to Facilities Management. In this section, an overview of BIM-IoT integration in the several FM core competencies is provided, and areas where further research is required within the scope of each core competence are suggested.

5.1. FM Core Competence: Finance and Business

The Finance and Business core competence concerns economic aspects, and it deals both with significant financial investment and operational expense. The only article concerning this competence [47] proposes a framework in which blockchain technology, smart sensors, smart contract and BIM are integrated. The proposed framework is meant to guide IT developers to design and implement an automated payment system (based on these new technologies) that aims to solve the security of payment problems. This application of multiple advanced technologies simultaneously and its related workflow are new to the current body of knowledge from both technical and managerial perspectives. In the article, smart sensors, at critical points across the entire supply-chain, provide live location and status information automatically onto a BIM model. Furthermore, smart sensor data are also stored on the blockchain network, providing an alternative system that will allow automated payment of fulfilled contractual obligations, resolving late-payment or non-payment-related issues.

Although this research's findings have undeniable advantages, this study is based on a specific blockchain platform. Further studies could adopt other blockchain platforms more suitable in upholding the security of payment. Furthermore, the research does not consider human tampering to commit fraud during the process. Even the authors suggested that subsequent studies should also consider fraud or any other human interventions that may influence systems operation. Hence, additional security layers and/or network security techniques should be investigated.

Finally, a possible main limitation of this framework hindering its adoption in the construction industry is the need for readily available money. The framework, providing automatic payment upon completion of the work, would jam in the case of lack of funds. If the client were temporarily experiencing a shortage of money in the course of the process, the automated payment would be blocked and the entire process would be interrupted.

Smart contracts and blockchain technology will undoubtedly be two essential elements in the future of FM. Future research should focus on these new technologies and challenges presented by them during the facility's whole life cycle. Several blockchain platforms should be investigated to provide the most suitable and secure solutions to the issues addressed.

5.2. FM Core Competence: Human Factor

This core competence focuses on protecting the environment and the people who use the facility, minimising risks and liabilities and positively impacting all stakeholders. All the articles belonging to this competence concern indoor environmental monitoring. Four out of seven articles [48,51–53] are on air quality monitoring. Two articles, [49] and [50], are about thermal comfort. Zaballos et al. (2020) [54] discuss environmental monitoring and emotion detection to provide insights into spaces' comfort level. Almost all articles focus their attention on the BIM–Wireless Sensors Network (WSN) connection, aiming to visualise real-time sensors data on the BIM model. The only exception is the research conducted by Zhong et al. (2018) [51], where the BIM model is used to extract building information stored in a tabular format and converted into ontology instances.

Table 9 shows the type of monitored data in each article.

Table 9. Human factor core competence: type of sensors used in studies on BIM–Wireless Sensors Network (WSN) integration for indoor environmental monitoring.

Reference	Scope	Issue	Sensors
Marzouk et al. (2014)	Indoor Environmental monitoring	Air quality	Temperature Particulate Matter
Zhong et al. (2018)	Indoor Environmental monitoring	Air quality	Temperature Humidity Noise Light Gas (CO, CO_2, Radon, Methane)
Ma et al. (2019)	Indoor Environmental monitoring	Air quality	Temperature Humidity Wind speed around person
Lin et al. (2020)	Indoor Environmental monitoring	Air quality	Carbon Monoxide Temperature Humidity
Marzouk et al. (2014)	Indoor Environmental monitoring	Thermal comfort	Temperature Humidity
Natephra et al. (2017)	Indoor Environmental monitoring	Thermal comfort	Temperature Thermographic camera
Zaballos et al. (2020)	Indoor Environmental monitoring	Air quality Thermal comfort	Temperature Humidity Noise Light CO, CO_2, TVOC

The integration between BIM and WSN offers great advantages to the monitoring systems developed in the various research studies. Through this integration, it is possible to better visualise a multitude of data relating to environmental monitoring and associated with multiple elements and spaces. Following this integration and creating the database containing all environmental data (e.g., temperature, humidity, light, noise, etc.), it is possible not only to monitor thermal/air quality problems to ensure comfort for users but also to detect the need for maintenance of building components.

However, during these processes, interoperability between different information systems and information sharing between various stakeholders remains challenging. Management of these heterogeneous data should be further investigated. Moreover, battery capacity and operation duration could be a significant limitation of a WSN. Therefore, it is necessary to consider adopting high-capacity batteries or a fixed power source for long-term operation.

To conclude, protecting the environment in which people live/work is certainly among the priorities that FM will have to face in the near future. Although the use of new technologies and sensors is widespread and certainly not new, the main challenge for this (but also other) core competencies is data/information interoperability. Finally, a novelty that emerged in this review is the improvement of the comfort level in facilities spaces through users emotion detection. In this direction, more effort should be focused to better fit building spaces to users.

5.3. FM Core Competence: Leadership and Strategy

This core competence focuses on aligning the facility portfolio with the organisation's missions and available resources. According to IFMA [13], sub-competencies in "Leadership and Strategy" include:

1. strategic planning and alignment with the organisation requirements;
2. policies, procedures and compliance;
3. individual and team management;
4. relationship and conflict management;
5. change management;
6. corporate social responsibility;
7. political, social, economic and industry factors affecting facility management.

There are few studies on this competence as for the previous one. After refining the query, only two studies remained (Table 8). Both articles deal with "decision-making" from two different points of view. Niu et al. (2016) [55] discuss several scenarios about using smart construction objects and their augmented capabilities of sensing, processing, computing, networking and reacting to alleviate human beings' incapability in decision-making. The Industry Foundation Classes (IFC) format is adopted to represent these objects in a virtual environment. With their innovative properties, smart construction objects can contribute to data collection and information processing and make autonomous decisions, eliminating human errors in the process and saving time. Although smart construction objects have undeniable advantages, there are still several limitations and challenges to fully exploit their potential, particularly cultural changes, new costs, Artificial Intelligence (AI) acceptance and organisation readiness.

On the other hand, Chang et al. (2018) [56] try to support complex decisions requiring interdisciplinary information using sensor data and the BIM model. Their research also deals with the design of a common platform allowing communication among sensors with different protocols and how visualisation may help make energy-saving management decisions. This visualisation allows us to see different values distribution in different contexts and make appropriate adjustments in each context. In addition, in this core competence, the key point is data/information integration from different sources. In the near future, this is undoubtedly the main problem that researchers will have to face due to the multiple and varied data sources and platforms.

5.4. FM Core Competence: Operations and Maintenance (O&M)

An important role in FM is to manage operations and maintenance of the facility. To do this, a good knowledge of building systems, structure, interiors and exteriors is required to ensure that systems operate efficiently, reliably, safely and in compliance with standards and regulations.

This core competence is one of the most investigated, and one of the earliest studies was conducted by Rio et al. (2013) [57]. The review showed a high growth rate in this category: ten out of fifteen articles were published in the past two years.

Among the sixteen reviewed articles in this category, nine [57–63,65,70] are about Structural Health Monitoring (SHM). BIM–sensor integration for SHM has been addressed since 2013, and interest in this topic has remained constant over the years. Through data-driven SHM techniques, it is possible to improve information management on structures health, safety and hazard mitigation. However, traditional approaches are insufficient to manage a large amount of data and information to conduct systematic decision-making for future maintenance.

The first attempt to create a connection between BIM and real-time data was made in 2013 by Rio et al. [57]. In their research, sensors data are stored within the BIM model. This strategy, however, could prove counterproductive as too many data from different types of sensors could weigh down the model.

Subsequent studies [58–63,65] propose an information modelling framework for supporting SHM, which includes an external database to facilitate storage, sharing and utilisation of gathered data. Authors, in their studies, propose approaches that support dynamic visualisation (within the BIM model) of some key structural performance parameters and enable continuous updating and long-term data management, generating models compliant with the IFC standard.

Such tools aim to facilitate decision-making on maintenance and risk management, avoiding manual errors resulting from visual inspection of the structures.

Furthermore, in their study, Fitz, Theiler and Smarsly [63] introduce the concept of the Cyber-Physical System (CPS) and present a metamodel for describing it. In their paper, communication-related properties and behaviour of CPS applied for SHM are described. Moreover, system components relevant to communication are specified. Then, the metamodel to formally define a CPS is proposed and mapped into the IFC schema.

On the other hand, the remaining articles that do not deal with SHM address equipment maintenance [66–68] and space management [64,69,71,72]. Here too, collected sensors data are stored in an external database.

The most relevant work in this area is, probably, the research of Cheng et al. [66]. They developed a data-driven predictive maintenance framework based on BIM, IoT and machine learning algorithms. Both Artificial Neural Network (ANN) and Support Vector Machine (SVM) are used to predict Mechanical, Electrical and Plumbing (MEP) components' future conditions with reasonably accurate results. Even if other prediction methods are taken into consideration, the proposed framework has significant implications: (a) fault alarming in an early stage avoiding failures; (b) future condition prediction (knowing in advance the failure timing); (c) minimising or avoiding overtime costs by preparing maintenance materials and tools ahead of time.

Articles that deal with management and maintenance services [64,69] focus primarily on occupancy control even if these systems are not always reliable due to their difficulty in counting people in crowded spaces.

In the O&M context, a first conclusion may be made: reviewed articles suggest that future research should focus on facing challenges presented by managing and visualising data acquired during the whole life cycle of the facility, not only during a single phase. Data-rich BIM models will be necessary to support facilities monitoring and applications fully.

Furthermore, many proprietary file formats are used in most articles. To streamline workflows and improve interoperability, it may be appropriate to increase the use of open formats.

Finally, further studies are required to automatically identify critical locations in which sensors are needed, types of sensors required to monitor critical elements and sensors data integration to improve O&M management.

5.5. FM Core Competence: Project Management

Another essential core skill in FM is Project Management (PM). Projects can vary in scope, complexity, duration and financial risk. According to IFMA, sub-competencies of PM include planning and design, execution and delivery, and evaluation.

Most of the articles concerning the PM [73–79] deal with the topics of real-time tracking of personnel, materials and equipment to enhance the security, safety, quality control, logistics and productivity monitoring. To do this, BIM and Radio Frequency IDentification (RFID) are the most used technologies [73,74,76–78] to implement localisation of people and objects. The proposed systems have a reliable accuracy rate, and RFID localisation systems have great potential in practical applications and could improve resource allocation efficiency and decrease human errors. Instead, Park et al. (2017) [75] developed a tracking system based on the integration of Bluetooth Low Energy (BLE) technology, motion sensors and BIM. This integration aims to achieve more accurate tracking that reduces and compensates for the sensors' errors.

On the other hand, Hamooni et al. (2020) [80] proposed a method that uses BIM interoperability and wireless sensors to monitor concrete maturity and control the concrete formwork process. BIM allows for the calculation of formwork removal time based on the maturity and strength data collected from sensors inside the concrete. This system will allow the concrete placement process to be continuously monitored and controlled and the curing time before formwork removal to be reduced, thus affecting construction management and project controls by (a) reducing the time required to complete the work, (b) avoiding project delays and (c) lowering unnecessary formwork rental expenses.

In conclusion, the main technological challenges found are related to the location and coverage of the sensors network and the signal strength of the router/hotspot. A significant problem that could arise is the stability of networks for communicating information.

Future research may include improvement of these systems and platforms by incorporating more functions related to the PM sub-competencies and productive analysis (e.g., future workforce estimation or a deep investigation of impacts on the total cost and time of a construction project resulting from the use of BIM–WSN integration).

5.6. FM Core Competence: Quality

Quality is one of the less investigated core competencies. It concerns needs and expectations on the facility and facility's services, aiming to improve facility organisations' and service providers' performance.

Both the articles on this topic [82,83] concern the quality of building components/construction work to ensure that specifications are implemented according to the project. Digitising information allows detecting design errors or poor performance. Both research studies integrate BIM validation tools to assure BIM quality.

5.7. FM Core Competence: Real Estate and Property Management

"Real Estate and property management" core competence is about the management of physical assets to enhance users' experience to meet asset owners' strategic objectives and to optimise real estate value. It is one of the least investigated core competencies. Among the reviewed articles, only two of these belongs to real estate and property management competence. Notable is the article of Atazadeh et al. [84], which discusses the use of BIM for defining the legal ownership of IoT-generated data, which are part of the asset value. There are no specific regulations or laws that define the retrieval and use of IoT data considering the appropriate legal rights and responsibilities. Rights, restrictions and responsibilities related to the use of IoT data in multi-owned buildings could be better defined using the BIM environment.

To conclude, as also highlighted by Moretti et al. [85] in their article, future developments in FM aiming at Real Estate and property management should focus attention again on interoperability and openBIM methodology to support dynamic assets management applications. The main issue in this context is the scarce as-built information. Supporting data integration, open formats and interoperability makes it possible to achieve better solutions for building management.

5.8. FM Core Competence: Risk Management

Risk Management plays a central role in FM and, unsurprisingly, is among the core competencies most investigated by researchers worldwide.

The articles belonging to this core competence address various issues related to risk management, Table 10 groups them by topic. Most of the articles, twelve out of seventeen, are fairly distributed between fire risk issues and safety in the workplace.

All the research agrees that the integration of data between BIM and WSN will provide an invaluable result for future applications in managing users and workers' health and safety. Fire risk studies focus mainly on (a) defining the fire conditions as well as the location and types of relevant fire-extinguishing tools needed; (b) localisation of trapped occupants in a fire emergency scene; and (c) evacuation/rescue paths optimisation. Proposed workflows and algorithms are BIM-centred, where BIM is integrated to provide geometric information and a graphical interface for user interaction.

Table 10. Risk management core competence: articles grouped by topic addressed.

References	Topic
[86,88,90,94,95,99]	Fire risk
[87,89,92,93,96,98]	Workers/Users Health and Safety (H&S)
[91,100]	Multi disaster (earthquake, flooding, and fire) countermeasure
[97]	Emergency response of utility tunnels
[101,102]	Excavation risks

Relevant studies in this field have been conducted by Cheng et al. [90] and Chou et al. [95]. Their studies are quite similar and propose a system based on a Bluetooth sensor network that can be used (a) to early detect a fire (b) to plan evacuation/rescue routes and to guide building users in emergencies, (c) for dynamic 3D visualisation of fire events and (d) for bidirectional human-machine interactions to optimise evacuation/rescue efforts. The proposed systems could reduce the number of casualties, support the rescue process and emergency evacuation, and mitigate the panic among people in cases of fire.

Another interesting research study in "fire risk management" was conducted by Cheng et al. [99]. Their study proposes an approach for adaptive path planning against the rapid environmental changes in fires. To detect the number of people in a building space, the network uses real-time videos from Closed-Circuit Television (CCTV) cameras and deep learning algorithms. In addition, an IoT sensor network (detect temperature, carbon dioxide and carbon monoxide) is used to detect hazardous areas. The BIM model provides floor plan information, sensors location and a simplified visualisation model during evacuation. Eventually, research suggests that it is possible to evacuate people through AR devices along the shortest path while avoiding congested and hazardous areas.

Research studies concerning workers' and building users' health and safety have investigated the integration of BIM with several types of wireless sensors to provide a centralised database with updated real-time data throughout the building lifecycle, starting from the construction phase. Currently, safety monitoring practices primarily rely on "manual" observation, which is labour-intensive and error-prone [92]. Therefore, the impact of sensor-based safety management systems, coupled with the BIM environment, could improve health, safety and emergency management.

In conclusion, systems coupling BIM models and sensors can continuously monitor the built environment in an automated way. They can be used for various purposes: (a) to prevent accidents by notifying workers of incoming hazards; (b) to notify safety managers or site supervisors about unidentified or newly appearing threats; (c) to monitor the environmental conditions of a confined space; (d) to better manage emergencies (e.g., fires) by providing optimised escape (or rescue) routes.

However, more research needs to be conducted to make these systems interoperable with existing sensor systems and minimise computational times to avoid any delay in emergency response operations. Furthermore, these systems could automatically detect and document near misses to prevent better accidents and, thus, to improve safety further.

One of the major limitations is the sensors reliability and transmission over long distances, which can cause false alarms. Other important limitations are related to the accuracy of deployed devices, which may be reduced due to water presence, to the presence of fire and/or smoke, which could impact accuracy and signal propagation. Moreover, energy demands may limit continuously monitoring sensors if not wired. Eventually, these BIM-based systems' performances rely on the accuracy of the BIM model. Therefore, having an updated BIM model is essential.

5.9. FM Core Competence: Sustainability

Sustainability, which is a legal obligation in some countries, could also be considered as a social responsibility that often turns into an economic advantage for asset owners. Facility managers are expected to act in order to protect the environment and the people who use their facilities while supporting organisational effectiveness and minimising risks and liabilities. Subcompetencies of sustainability include energy management, water management, materials and consumables management, waste management and workplace and site management.

Sustainability is among the most investigated FM core competencies. Most of the articles concerning sustainability deal with how buildings' energy demand can be reduced through Information and Communication Technologies (ICT). Furthermore, the ICT application in several processes (e.g., BIM) and scenarios have been investigated. In most cases [52,103,104,106–108,110–117,119] BIM is used to process or display buildings' geometric data, FM data and energy data collected through sensors. Among these articles, References [104,111,113,115–117,119] focus on users' behaviours. These researches aim to raise users' awareness of energy efficiency and consider building users as a primary factor to improve energy efficiency and IEQ. Results put forth the use of real-time monitoring systems and suggest a controlled interaction among users and heating systems to improve energy performances and comfort.

An interesting approach to interact with users has been made by Francisco et al. [116]. They propose a method of combining data and graphic representation through spatial and colour coding techniques in BIM. Through this type of information representation, users can access complex information through a simple interface. In this way, it is possible to improve the interpretation of energy data and increase the user's involvement in the building's management, consequently improving building consumption, comfort and health. Furthermore, the proposed method could be applied to other factors such as water consumption, room temperature or indoor air quality.

Only two studies [52,114] deal with/involve artificial neural networks (ANNs) in sustainability, probably because it is a relatively new topic in the AECO sector. The study of McGlinn et al. is relevant. [114]. They propose an intelligent monitoring and control interface for efficient energy management using BIM and Semantic Web to integrate smart buildings, sensors and software components like artificial neural network (ANN) and genetic algorithms (GA). This interface provides suggestions based on the building's sensor measurements and proposes these suggestions to the Facility Manager. However, there are still issues related to interface usability for non-technical users.

The other two studies dealing with sustainability discuss: (a) a framework integrating the information necessary for green buildings design and their automated evaluation process [105] and (b) a BIM–RFID-based approach with the potential to improve resource reuse and efficiency [109]. Although through the two approaches presented in the articles mentioned above, it is possible to gain advantages in the design processes of Green Buildings, it is evident that research in these fields is still at an early stage.

When discussing sustainable approaches aimed at controlling energy consumption in a building, it is impossible not to mention the Building Energy Management Systems (BEMSs). A BEMS can fully monitor and control the building's energy needs through building energy data collection, performance analysis and equipment control [139]. Through better energy management in a building, a BEM not only reduces energy consumption and costs but also improves occupants' comfort [139]. Conceptually, a BEMS architecture has different layers: a sensor/actuation layer, a computational layer, an application layer and, in some cases, also a user interaction layer [114].

Hence, on the one hand, the BIM model provides a series of static data relating to the building (not only geometric and spatial data but also other information according to the BIM's several dimensions). On the other hand, the BEM system takes the role of collecting data from sensors in the building on-site. The synergy between these two environments (BIM–BEM) can positively affect building energy management, especially by users' involvement. Among selected articles, the first attempt at BIM-BEM integration dates back to 2013 with the research carried out by Osello et al. [104]. They developed an ICT infrastructure made of heterogeneous monitoring and actuation devices to reduce energy consumption. Finally, they used BIM and interoperability to process and visualise all data essential for energy simulations and for FM. Other studies, from Lee et al. [112] and McGlinn et al. [114], show that BIM is a useful approach for the visual representation, management and exchange of information on all aspects of a building. In particular, in Lee's research, BIM was used to develop an energy management platform. In their study, BIM was used to visualise gathered environmental and energy consumption data. In this way, facility managers could better manage buildings energy consumption and control buildings' equipment.

Another significant attempt at BIM–BEM integration has been made by Kang (2020) [118]. Kang, in his research, proposes a BIM-based Human Machine Interface (HMI) framework for space-based energy management. The proposed framework links data between BIM and BEMS, which are heterogeneous systems, aiming at space-based real-time energy monitoring. Furthermore, as it is challenging to use a BIM data structure if it does not fit into the energy management system, this researcher also defines requirements for developing a BIM database suitable for the proposed framework.

In conclusion, although there is much to be done in built environment sustainability challenges, four major steps should be accomplished: (a) fine-tuning of the interaction between environmental sensors data and Artificial Intelligence (AI) or optimisation algorithms; (b) developing sustainable and innovative user interaction strategies; (c) focusing attention on other sustainability sub-competencies (e.g., water management, materials and consumables management, waste management); (d) aiming at BIM–BEM integration, overcoming problems due to the differentiation of communication protocols.

5.10. FM Core Competence: Information and Technology Management

Although the whole topic of BIM–IoT integration could be discussed in this section, only articles concerning sub-competencies such as technology needs assessment and implementation, maintenance and upgrade of technology systems or protection and cybersecurity are addressed here. Some of the analysed articles may be associated with other FM competencies, but they are discussed in this FM core competence if:

a. the research on BIM–IoT integration encompasses more than one FM competence;
b. the article discusses the integration of technologies such as Augmented Reality (AR)/Mixed Reality (MR)/Virtual Reality (VR).

Many of the reviewed articles suggest no generic approach to assist in creating software services and applications combining sensor data with BIM models. Articles address the engineering complexity associated with integrating sensor data with BIM to facilitate real-time operational performance information management and permit proactive operational and maintenance decisions in many ways. Only three articles [123,127,131] discuss the development of collaborative BIM-based AR/MR/VR approaches. Interesting research has been carried out by El Ammari et al. [127], who developed a Mixed-Reality framework for facilities management with two modules: a field AR module and an office Immersive Augmented Virtuality (IAV) module. These modules can be used independently or combined using interactive visual collaboration, with an improvement in field task efficiency.

Another noteworthy research study was carried out by Kazado et al. (2019) [128], who presented three approaches for BIM-sensors integration to enable visualisation and analysis of real-time and historical data. Despite being probably the first work using Autodesk Navisworks software to implement a user-friendly interface that integrates the existing building sensor technology and BIM process, the use of a closed data format (Autodesk's files format) instead of an open one could be a limitation.

Most of the studies highlight the risk of losing competitiveness both on the local and international markets if stakeholders in the construction sector slow down the adoption of new technology. The construction industry appears to be already outdated when compared to other industrial sectors. Nevertheless, according to the articles, stakeholders seem reluctant to invest, especially in costly innovative technological devices. Therefore, many researchers aim to reduce the initial investment costs while proposing innovative solutions that bring added value to the FM processes.

6. Conclusions

Although still in its infancy, the construction sector's digitisation process is underway, aiming to create an ever-larger network of cyber-physical connections, supported by the abundance of sensorized and networked elements. The analysis of data generated by sensorized building components and systems will allow using connected digital models to improve future design and increase the environmental, safety and financial performance of the digitally built environment.

This document provides an overview of BIM and IoT integration in FM. From a query on Scopus and Web of Science with more than 900 results, 99 articles were identified and reviewed as the most relevant references. Existing gaps and future research directions were outlined.

BIM now supports many technological advances that the industry is witnessing, albeit with some limitations. Although BIM is widely used in the building design phase, there is still much to do for its use in Facility Management. Nevertheless, BIM can be considered a natural interface for IoT/real-time data implementation. Several researchers have begun to explore the potential synergy between these two environments.

From the literature review, it emerges that the BIM and IoT integration research is in an early phase. Most research works are still in the conceptual stage, even though some studies are quite thorough and propose solutions tested in real-world applications. The main obstacles preventing the uptake of these new technologies include (1) in most cases, the lack of a BIM approach that meets the information requirements and fully exploits the potential of the digital model; (2) the fragmented nature of the AEC sector; and (3) shortage of real-life use cases demonstrating potential benefits.

General remarks found on BIM for FM are related to the need to

1. enhance the interoperability of data from as-designed to as-built for FM purposes;
2. review and improve IFC open standards and data specifications to satisfy data and information required for FM.

Furthermore, one of the main challenges in BIM–IoT integration is coupling dynamic real-time data to the model database. In this context, future studies are needed to

1. find a standardised way to integrate and manage data;
2. enhance further exploration in cloud computing;
3. improve other digital technologies such as Augmented, Virtual and Mixed Reality and their application in the AEC sector, integrating them with BIM

BIM–IoT data integration has a new added value in the market: the physical object is a product that carries information throughout its life cycle. This will significantly help the construction industry, which, mimicking more industrialised sectors, has just begun its journey from being product-oriented to service-oriented. However, to take advantage of this transformation, the integration of data into BIM models needs to be managed in the best possible way.

BIM and IoT studies are often based on proprietary files and closed ecosystems, where information is not yet shared openly among stakeholders. Hence, subsequent studies within the BIM-IoT integration domain should focus their attention on open data and open communication standards.

On the other hand, WSN could be considered the IoT solution for monitoring and recording the physical condition of buildings and environmental monitoring management. Research hass proved that both high costs and ineffectiveness of WSN devices can be avoided if information requirements (data types, data frequencies, WSN devices' location, etc.) are appropriately set at the very beginning of the asset lifecycle.

The major problems encountered in the use of WSN concern:

1. signal transmission: the number of devices necessary for the correct transmission of data and information can influence costs or be limited by the type of construction;
2. powering devices: batteries may not be efficient enough in continuously monitored devices, and the main power supply cannot always reach all devices.

In conclusion, this review highlights four key areas to be further studied:

1. Learning from errors. Future asset design should be influenced by lessons learned from existing ones. Architects and engineers rarely study buildings' performances or act on occupant feedback (post-occupancy evaluations) once they are handed over to the client. Therefore, it is very probable that errors made are often replicated in other future building design developments. Data coming from the use phase of the assets allows essential information to be collected to better guide the design phase, aiming for improvements in FM activities. However, few researchers have addressed the problem of handing back the information collected in the life cycle to the design team. There is no evidence in the literature about what information is needed or how best to collect and present it.
2. Exploiting new technologies. Advancement in Information and Communications Technology is giving the construction sectors hardware and software tools with unprecedented capabilities and with ever lower costs. First exploratory examples of the use of these technologies for district and cities have appeared, giving a new vision of the idea of smart cities. In this context, new research should focus on both adopting new technologies and finding the best way to satisfy the need for specific training of FM managers and workers. Additionally, although interoperability frameworks have already been investigated and developed, future research should address the potential of BIM to handle a dynamic environment and overcome the differentiation of communication protocols.
3. Application of machine learning algorithms to gather data to develop self-learning and self-improving algorithms to enhance building management. Edge computing and edge analytics seem to allow for an improved system, where data are used where they are produced.
4. User awareness/involvement through simplified interfaces/interactions. BIM remains a tool for experts, and hardly any users or FM managers are able to use the information it contains. Although research has proved that users' involvement is vital for more sustainable buildings, few studies collected real-time data involving asset users in buildings use and management. First research studies have proved that AR can improve building operations and maintenance, but there may still be ground for improvement in this field.

A deep review of 99 articles related to the eleven IFMA FM core competencies highlights four main knowledge gaps in the emerging sector of BIM and IoT integration for FM. These are related to the back-propagation of information from the use stage to the design one, to new technologies exploitation and final users' involvement in improving buildings sustainability. This may help further research advancement for studies to improve built environment management.

Author Contributions: Conceptualisation, A.M., M.C.D. and F.R.C.; methodology, A.M., M.C.D. and F.R.C.; software, A.M.; data curation, A.M.; writing—original draft preparation, A.M.; writing—review and editing, A.M., M.C.D. and F.R.C.; supervision, M.C.D. and F.R.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Haghsheno, S.; Deubel, M.; Spenner, L. Identification and description of relevant digital technologies for the construction industry. *Bauingenieur* **2019**, *94*, 45–55. [CrossRef]
2. Hossain, M.A.; Nadeem, A. Towards digitising the construction industry: State of the art of construction 4.0. In Proceedings of the ISEC 10: Interdependence between Structural Engineering and Construction Management, Chicago, IL, USA, 20–25 May 2019; pp. 1–6.
3. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
4. Blanco, J.; Mullin, A.; Pandya, K.; Sridhar, M. The new age of engineering and construction technology. *McKinsey Q.* **2017**, 1–16. [CrossRef]
5. McKinsey Global Institute. *Reinventing Construction: A Route To Higher Productivity*; McKinsey Global Institute: Chicago, IL, USA, 2017. [CrossRef]
6. Chung, S.W.; Kwon, S.W.; Moon, D.Y.; Ko, T.K. Smart facility management systems utilising open BIM and augmented/virtual reality. In Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC2018), Berlin, Germany, 20–25 July 2018.
7. Wong, J.K.W.; Ge, J.; He, S.X. Digitisation in facilities management: A literature review and future research directions. *Autom. Constr.* **2018**, *92*, 312–326. [CrossRef]
8. Cheng, J.C.P.; Chen, K.; Chen, W.; Li, C.T. A Bim-Based Location Aware Ar Collaborative Framework for Facility Maintenance Management. *J. Inf. Technol. Constr.* **2019**, *24*, 30–39. Available online: http://www.itcon.org/2019/19 (accessed on 20 February 2021).
9. Glaessgen, E.; Stargel, D. The Digital Twin Paradigm for Future NASA and US Air Force Vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA, Honolulu, HI, USA, 23–26 April 2012. [CrossRef]
10. Bonci, A.; Carbonari, A.; Cucchiarelli, A.; Messi, L.; Pirani, M.; Vaccarini, M. A cyber-physical system approach for building efficiency monitoring. *Autom. Constr.* **2019**, *102*, 68–85. [CrossRef]
11. Love, P.E.D.; Matthews, J. The 'how' of benefits management for digital technology: From engineering to asset management. *Autom. Constr.* **2019**, *107*, 102930. [CrossRef]
12. *ISO 41011:2017. International Standard Facility Management—Vocabulary*; ISO: Geneva, Switzerland, 2017.
13. International Facility Management Association (IFMA). Certified Facility Manager®(CFM®)—Competency Guide. 2018. Available online: https://www.ifma.org/about/what-is-facility-management (accessed on 20 February 2021).
14. Omar, N.S.; Najy, H.I.; Ameer, H.W. Developing of Building Maintenance Management by Using BIM. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 1371–1383. Available online: https://www.iaeme.com/MasterAdmin/uploadfolder/IJCIET-09-11-132/IJCIET-09-11-132.pdf (accessed on 20 February 2021).
15. Vanier, D.J. Advanced asset management: Tools and techniques. In Proceedings of the APWA International Public Works Congress NRCC/CPWA Seminar Series "Innovations in Urban Infrastructure", Louisville, KY, USA, 9 September 2000.
16. Cheng, J.C.P.; Chen, W.; Tan, Y.; Wang, M. A BIM-Based Decision Support System Framework for Predictive Maintenance Management of Building Facilities. In Proceedings of the 16th International Conference on Computing in Civil and Building Engineering (ICCCBE2016), Osaka, Japan, 6–8 July 2016; pp. 711–718.
17. Xiao, Y.-Q.; Li, S.-W.; Hu, Z.-Z. Automatically Generating a MEP Logic Chain from Building Information Models with Identification Rules. *Appl. Sci.* **2019**, *9*, 2204. [CrossRef]
18. Wanigarathna, N.; Jones, K.; Bell, A.; Kapogiannis, G. Building information modelling to support maintenance management of healthcare built assets. *Facilities* **2019**, *37*, 415–434. [CrossRef]
19. Rajput, S.; Singh, S.P. Industry 4.0—Challenges to implement circular economy. *Benchmarking* **2019**. [CrossRef]
20. De Sousa Jabbour, A.B.L.; Jabbour, C.J.C.; Filho, M.G.; Roubaud, D. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. *Ann. Oper. Res.* **2018**, *270*, 273–286. [CrossRef]
21. Ashworth, S.; Tucker, M.; Druhmann, C.K. Critical success factors for facility management employer's information requirements (EIR) for BIM. *Facilities* **2019**, *37*, 103–118. [CrossRef]
22. NIBS. National BIM Guide for Owners. NIBS, 2017; 46p, Available online: https://www.nibs.org/files/pdfs/NIBS_BIMC_NationalBIMGuide.pdf (accessed on 20 February 2021).
23. Hilal, M.; Maqsood, T.; Abdekhodaee, A. A hybrid conceptual model for BIM in FM. *Constr. Innov.* **2019**, *19*, 531–549. [CrossRef]
24. *ISO 19650-2:2018. Organization and Digitisation of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling*; ISO: Geneva, Switzerland, 2018.
25. BIM Forum. Level of Development (LOD) Specification Part I & Commentary, Bim-Bep. 2019; 254p, Available online: https://bimforum.org/resources/Documents/BIMForum_LOD_2019_reprint.pdf (accessed on 20 February 2021).
26. Love, P.E.D.; Simpson, I.; Hill, A.; Standing, C. From justification to evaluation: Building information modeling for asset owners. *Autom. Constr.* **2013**, *35*, 208–216. [CrossRef]
27. Becerik-Gerber, B.; Jazizadeh, F.; Li, N.; Calis, G. Application Areas and Data Requirements for BIM-Enabled Facilities Management. *J. Constr. Eng. Manag.* **2012**, *138*, 431–442. [CrossRef]

28. Bortoluzzi, B.; Efremov, I.; Medina, C.; Sobieraj, D.; McArthur, J.J. Automating the creation of building information models for existing buildings. *Autom. Constr.* **2019**, *105*, 102838. [CrossRef]
29. Matarneh, S.T.; Danso-Amoako, M.; Al-Bizri, S.; Gaterell, M.; Matarneh, R.T. BIM for FM: Developing information requirements to support facilities management systems. *Facilities* **2019**, *38*, 378–394. [CrossRef]
30. Wang, Y.; Wang, X.; Wang, J.; Yung, P.; Jun, G. Engagement of facilities management in design stage through BIM: Framework and a case study. *Adv. Civ. Eng.* **2013**, *2013*, 189105. [CrossRef]
31. Ismail, Z.A. An Integrated Computerised Maintenance Management System (I-CMMS) for IBS building maintenance. *Int. J. Build. Pathol. Adapt.* **2019**, *37*, 326–343. [CrossRef]
32. Chen, W.; Chen, K.; Cheng, J.C.P.; Wang, Q.; Gan, V.J.L. BIM-based framework for automatic scheduling of facility maintenance work orders. *Autom. Constr.* **2018**, *91*, 15–30. [CrossRef]
33. Golabchi, A.; Akula, M.; Kamat, V. Automated building information modeling for fault detection and diagnostics in commercial HVAC systems. *Facilities* **2016**, *34*, 233–246. [CrossRef]
34. Munir, M.; Kiviniemi, A.; Jones, S.W. Business value of integrated BIM-based asset management. *Eng. Constr. Arch. Manag.* **2019**, *26*, 1171–1191. [CrossRef]
35. Dixit, M.K.; Venkatraj, V.; Ostadalimakhmalbaf, M.; Pariafsai, F.; Lavy, S. Integration of facility management and building information modeling (BIM). *Facilities* **2019**, *37*, 455–483. [CrossRef]
36. Pärn, E.A.; Edwards, D.J.; Sing, M.C.P. The building information modelling trajectory in facilities management: A review. *Autom. Constr.* **2017**, *75*, 45–55. [CrossRef]
37. Patacas, J.; Dawood, N.; Vukovic, V.; Kassem, M. BIM for facilities management: Evaluating BIM standards in asset register creation and service life planning. *J. Inf. Technol. Constr.* **2015**, *20*, 313–331.
38. Asghari, P.; Rahmani, A.M.; Javadi, H.H.S. Internet of Things applications: A Systematic Review. *Comput. Netw.* **2019**, *148*, 241–261. [CrossRef]
39. Gubbi, J.; Buyya, R.; Marusic, S.; Palaniswami, M. Internet of Things (IoT): A vision, architectural elements, and future directions. *Futur. Gener. Comput. Syst.* **2013**, *29*, 1645–1660. [CrossRef]
40. Pradeep, S.; Kousalya, T.; Suresh, K.M.A.; Edwin, J. IoT and its connectivity challenges in smart home. *Int. Res. J. Eng. Technol.* **2016**, *3*, 1040–1043. Available online: http://www.indjst.org/index.php/indjst/article/view/109387 (accessed on 20 February 2021).
41. Rizal, R.; Hikmatyar, M. Investigation Internet of Things (IoT) Device using Integrated Digital Forensics Investigation Framework (IDFIF). *J. Phys. Conf. Ser.* **2019**, *1179*, 012140. [CrossRef]
42. Rondeau, E.P.; Brown, R.K.; Lapides, P.D. *Facility Management*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
43. Jeon, Y.; Cho, C.; Seo, J.; Kwon, K.; Park, H.; Oh, S.; Chung, I.J. IoT-based occupancy detection system in indoor residential environments. *Build. Environ.* **2018**, *132*, 181–204. [CrossRef]
44. Rafsanjani, H.N.; Ghahramani, A. Towards utilising internet of things (IoT) devices for understanding individual occupants' energy usage of personal and shared appliances in office buildings. *J. Build. Eng.* **2020**, *27*, 100948. [CrossRef]
45. Madrid, N.; Boulton, R.; Knoesen, A. Remote monitoring of winery and creamery environments with a wireless sensor system. *Build. Environ.* **2017**, *119*, 128–139. [CrossRef]
46. Aria, M.; Cuccurullo, C. Bibliometrix: An R-tool for comprehensive science mapping analysis. *J. Inf.* **2017**, *11*, 959–975. [CrossRef]
47. Chong, H.Y.; Diamantopoulos, A. Integrating advanced technologies to uphold security of payment: Data flow diagram. *Autom. Constr.* **2020**, *114*, 103158. [CrossRef]
48. Marzouk, M.; Abdelaty, A. BIM-based framework for managing performance of subway stations. *Autom. Constr.* **2014**, *41*, 70–77. [CrossRef]
49. Marzouk, M.; Abdelaty, A. Monitoring thermal comfort in subways using building information modelling. *Energy Build.* **2014**, *84*, 252–257. [CrossRef]
50. Natephra, W.; Motamedi, A.; Yabuki, N.; Fukuda, T. Integrating 4D thermal information with BIM for building envelope thermal performance analysis and thermal comfort evaluation in naturally ventilated environments. *Build. Environ.* **2017**, *124*, 194–208. [CrossRef]
51. Zhong, B.; Gan, C.; Luo, H.; Xing, X. Ontology-based framework for building environmental monitoring and compliance checking under BIM environment. *Build. Environ.* **2018**, *141*, 127–142. [CrossRef]
52. Ma, G.; Liu, Y.; Shang, S. A building information model (BIM) and artificial neural network (ANN) based system for personal thermal comfort evaluation and energy efficient design of interior space. *Sustainability* **2019**, *11*, 4972. [CrossRef]
53. Lin, Y.-C.; Cheung, W.-F. Developing WSN/BIM-Based Environmental Monitoring Management System for Parking Garages in Smart Cities. *J. Manag. Eng.* **2020**, *36*. [CrossRef]
54. Zaballos, A.; Briones, A.; Massa, A.; Centelles, P.; Caballero, V. A smart campus' digital twin for sustainable comfort monitoring. *Sustainability* **2020**, *12*, 9196. [CrossRef]
55. Niu, Y.; Lu, W.; Chen, K.; Huang, G.G.; Anumba, C. Smart construction objects. *J. Comput. Civ. Eng.* **2016**, *30*. [CrossRef]
56. Chang, K.-M.; Dzeng, R.-J.; Wu, Y.-J. An Automated IoT Visualization BIM Platform for Decision Support in Facilities Management. *Appl. Sci.* **2018**, *8*, 1086. [CrossRef]
57. Rio, J.; Ferreira, B.; Poças-Martins, J. Expansion of IFC model with structural sensors. *Inf. La Constr.* **2013**, *65*, 219–228. [CrossRef]

58. Zhang, Y.; Bai, L. Rapid structural condition assessment using radio frequency identification (RFID) based wireless strain sensor. *Autom. Constr.* **2015**, *54*, 1–11. [CrossRef]
59. Delgado, J.M.D.; Butler, L.J.; Gibbons, N.; Brilakis, I.; Elshafie, M.Z.E.B.; Middleton, C. Management of structural monitoring data of bridges using BIM. *Proc. Inst. Civ. Eng. Eng.* **2017**, *170*, 204–218. [CrossRef]
60. Jeong, S.; Hou, R.; Lynch, J.P.; Sohn, H.; Law, K.H. An information modeling framework for bridge monitoring. *Adv. Eng. Softw.* **2017**, *114*, 11–31. [CrossRef]
61. Delgado, J.M.D.; Butler, L.J.; Brilakis, I.; Elshafie, M.Z.E.B.; Middleton, C.R. Structural Performance Monitoring Using a Dynamic Data-Driven BIM Environment. *J. Comput. Civ. Eng.* **2018**, *32*. [CrossRef]
62. Boddupalli, C.; Sadhu, A.; Azar, E.R.; Pattyson, S. Improved visualisation of infrastructure monitoring data using building information modelling. *Struct. Infrastruct. Eng.* **2019**, *15*, 1247–1263. [CrossRef]
63. Fitz, T.; Theiler, M.; Smarsly, K. A metamodel for cyber-physical systems. *Adv. Eng. Inform.* **2019**, *41*, 100930. [CrossRef]
64. Mannino, A.; Moretti, N.; Dejaco, M.C.; Baresi, L.; Cecconi, F.R. Office building occupancy monitoring through image recognition sensors. *Int. J. Saf. Secur. Eng.* **2019**, *9*, 371–380. [CrossRef]
65. Valinejadshoubi, M.; Bagchi, A.; Moselhi, O. Development of a BIM-Based Data Management System for Structural Health Monitoring with Application to Modular Buildings: Case Study. *J. Comput. Civ. Eng.* **2019**, *33*, 1–16. [CrossRef]
66. Cheng, J.C.P.; Chen, W.; Chen, K.; Wang, Q. Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Autom. Constr.* **2020**, *112*, 103087. [CrossRef]
67. Kameli, M.; Sardroud, J.M.; Hosseinalipour, M.; Behruyan, M.; Ahmed, S.M. An application framework for development of a maintenance management system based on building information modeling and radio-frequency identification: Case study of a stadium building. *Can. J. Civ. Eng.* **2020**, *47*, 736–748. [CrossRef]
68. Ma, Z.; Ren, Y.; Xiang, X.; Turk, Z. Data-driven decision-making for equipment maintenance. *Autom. Constr.* **2020**, *112*, 103103. [CrossRef]
69. Moretti, N.; Cadena, J.D.B.; Mannino, A.; Poli, T.; Cecconi, F.R. Maintenance service optimisation in smart buildings through ultrasonic sensors network. *Intell. Build. Int.* **2021**, *13*, 4–16. [CrossRef]
70. O'Shea, M.; Murphy, J. Design of a BIM integrated structural health monitoring system for a historic offshore lighthouse. *Buildings* **2020**, *10*, 131. [CrossRef]
71. Xie, X.; Lu, Q.; Rodenas-Herraiz, D.; Parlikad, A.K.; Schooling, J.M. Visualised inspection system for monitoring environmental anomalies during daily operation and maintenance. *Eng. Constr. Archit. Manag.* **2020**, *27*, 1835–1852. [CrossRef]
72. Yin, X.; Liu, H.; Chen, Y.; Wang, Y.; Al-Hussein, M. A BIM-based framework for operation and maintenance of utility tunnels. *Tunn. Undergr. Space Technol.* **2020**, *97*, 103252. [CrossRef]
73. Costin, A.M.; Teizer, J.; Schoner, B. RFID and bim-enabled worker location tracking to support real-time building protocol control and data visualisation. *J. Inf. Technol. Constr.* **2015**, *20*, 495–517.
74. Fang, Y.; Cho, Y.K.; Zhang, S.; Perez, E. Case Study of BIM and Cloud-Enabled Real-Time RFID Indoor Localization for Construction Management Applications. *J. Constr. Eng. Manag.* **2016**, *142*. [CrossRef]
75. Park, J.W.; Chen, J.; Cho, Y.K. Self-corrective knowledge-based hybrid tracking system using BIM and multimodal sensors. *Adv. Eng. Inform.* **2017**, *32*, 126–138. [CrossRef]
76. Zhong, R.Y.; Peng, Y.; Xue, F.; Fang, J.; Zou, W.; Luo, H.; Ng, S.T.; Lu, W.; Shen, G.Q.P.; Huang, G.Q. Prefabricated construction enabled by the Internet-of-Things. *Autom. Constr.* **2017**, *76*, 59–70. [CrossRef]
77. Chen, K.; Xu, G.; Xue, F.; Zhong, R.Y.; Liu, D.; Lu, W. A Physical Internet-enabled Building Information Modelling System for prefabricated construction. *Int. J. Comput. Integr. Manuf.* **2018**, *31*, 349–361. [CrossRef]
78. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]
79. Tagliabue, L.C.; Ciribini, A.L.C. A BIM Based IoT Approach to the Construction Site Management. *Bo-Ricerche E Progett. Per Territ. La Citta E L Archit.* **2018**, *9*, 136–145.
80. Hamooni, M.; Maghrebi, M.; Sardroud, J.M.; Kim, S. Extending BIM Interoperability for Real-Time Concrete Formwork Process Monitoring. *Appl. Sci.* **2020**, *10*, 1085. [CrossRef]
81. Pan, Y.; Zhang, L. A BIM-data mining integrated digital twin framework for advanced project management. *Autom. Constr.* **2021**, *124*, 103564. [CrossRef]
82. Hernández, J.L.; Lerones, P.M.; Bonsma, P.; van Delft, A.; Deighton, R.; Braun, J.D. An IFC interoperability framework for self-inspection process in buildings. *Buildings* **2018**, *8*, 32. [CrossRef]
83. Martinez, P.; Ahmad, R.; Al-Hussein, M. A vision-based system for pre-inspection of steel frame manufacturing. *Autom. Constr.* **2019**, *97*, 151–163. [CrossRef]
84. Atazadeh, B.; Olfat, H.; Rismanchi, B.; Shojaei, D.; Rajabifard, A. Utilising a building information modelling environment to communicate the legal ownership of internet of things-generated data in multi-owned buildings. *Electronics* **2019**, *8*, 1258. [CrossRef]
85. Moretti, N.; Xie, X.; Merino, J.; Brazauskas, J.; Parlikad, A.K. An openbim approach to iot integration with incomplete as-built data. *Appl. Sci.* **2020**, *10*, 8287. [CrossRef]
86. Shiau, Y.-C.; Tsai, Y.-Y.; Hsiao, J.-Y.; Chang, C.-T. Development of building fire control and management system in BIM environment. *Stud. Inform. Control.* **2013**, *22*, 15–24. [CrossRef]

87. Arslan, M.; Riaz, Z.; Kiani, A.K.; Azhar, S. Real-Time Environmental Monitoring, Visualisation And Notification System For Construction H&S Management. *J. Inf. Technol. Constr.* **2014**, *19*, 72–91. Available online: http://www.itcon.org/2014/4 (accessed on 20 February 2021).
88. Li, N.; Becerik-Gerber, B.; Krishnamachari, B.; Soibelman, L. A BIM centered indoor localisation algorithm to support building fire emergency response operations. *Autom. Constr.* **2014**, *42*, 78–89. [CrossRef]
89. Riaz, Z.; Arslan, M.; Kiani, A.K.; Azhar, S. CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined spaces. *Autom. Constr.* **2014**, *45*, 96–106. [CrossRef]
90. Cheng, M.Y.; Chiu, K.C.; Hsieh, Y.M.; Yang, I.T.; Chou, J.S.; Wu, Y.W. BIM integrated smart monitoring technique for building fire prevention and disaster relief. *Autom. Constr.* **2017**, *84*, 14–30. [CrossRef]
91. Park, S.; Hong, C. Roles and scope of system interface in integrated control system for multi disaster countermeasure. *Int. J. Saf. Secur. Eng.* **2017**, *7*, 361–366. [CrossRef]
92. Park, J.; Kim, K.; Cho, Y.K. Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors. *J. Constr. Eng. Manag.* **2017**, *143*. [CrossRef]
93. Riaz, Z.; Parn, E.A.; Edwards, D.J.; Arslan, M.; Shen, C.; Pena-Mora, F. BIM and sensor-based data management system for construction safety monitoring. *J. Eng. Des. Technol.* **2017**, *15*, 738–753. [CrossRef]
94. Beata, P.A.; Jeffers, A.E.; Kamat, V.R. Real-Time Fire Monitoring and Visualization for the Post-Ignition Fire State in a Building. *Fire Technol.* **2018**, *54*, 995–1027. [CrossRef]
95. Chou, J.S.; Cheng, M.Y.; Hsieh, Y.M.; Yang, I.T.; Hsu, H.T. Optimal path planning in real time for dynamic building fire rescue operations using wireless sensors and visual guidance. *Autom. Constr.* **2019**, *99*, 1–17. [CrossRef]
96. Parn, E.A.; Edwards, D.; Riaz, Z.; Mehmood, F.; Lai, J. Engineering-out hazards: Digitising the management working safety in confined spaces. *Facilities* **2019**, *37*, 196–215. [CrossRef]
97. Yu, G.; Mao, Z.; Hu, M.; Li, Z.; Sugumaran, V. BIM+ Topology Diagram-Driven Multiutility Tunnel Emergency Response Method. *J. Comput. Civ. Eng.* **2019**, *33*, 1–19. [CrossRef]
98. Asadzadeh, A.; Arashpour, M.; Li, H.; Ngo, T.; Bab-Hadiashar, A.; Rashidi, A. Sensor-based safety management. *Autom. Constr.* **2020**, *113*, 103128. [CrossRef]
99. Cheng, J.C.P.; Chen, K.; Wong, P.K.-Y.; Chen, W.; Li, C.T. Graph-based network generation and CCTV processing techniques for fire evacuation. *Build. Res. Inf.* **2021**, *49*, 179–196. [CrossRef]
100. Lei, Y.; Rao, Y.; Wu, J.; Lin, C.H. BIM based cyber-physical systems for intelligent disaster prevention. *J. Ind. Inf. Integr.* **2020**, *20*, 100171. [CrossRef]
101. Lin, S.S.; Shen, S.L.; Zhou, A.; Xu, Y.S. Risk assessment and management of excavation system based on fuzzy set theory and machine learning methods. *Autom. Constr.* **2021**, *122*, 103490. [CrossRef]
102. Tian, W.; Meng, J.; Zhong, X.J.; Tan, X. Intelligent Early Warning System for Construction Safety of Excavations Adjacent to Existing Metro Tunnels. *Adv. Civ. Eng.* **2021**, *2021*, 8833473. [CrossRef]
103. Goekce, H.U.; Goekce, K.U. Holistic system architecture for energy efficient building operation. *Sustain. CITIES Soc.* **2013**, *6*, 77–84. [CrossRef]
104. Osello, A.; Acquaviva, A.; Aghemo, C.; Blaso, L.; Dalmasso, D.; Erba, D.; Fracastoro, G.; Gondre, D.; Jahn, M.; Macii, E.; et al. Energy saving in existing buildings by an intelligent use of interoperable ICTs. *Energy Effic.* **2013**, *6*, 707–723. [CrossRef]
105. Cheng, J.C.P.; Das, M. A bim-based web service framework for green building energy simulation and code checking. *J. Inf. Technol. Constr.* **2014**, *19*, 150–168. Available online: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84907376890&partnerID=40&md5=2f62f7e068a13717acf819b1e0948d62 (accessed on 20 February 2021).
106. Gökçe, H.U.; Gökçe, K.U. Integrated system platform for energy efficient building operations. *J. Comput. Civ. Eng.* **2014**, *28*, 1–11. [CrossRef]
107. Goekce, H.U.; Goekce, K.U. Multi dimensional energy monitoring, analysis and optimisation system for energy efficient building operations. *Sustain. CITIES Soc.* **2014**, *10*, 161–173. [CrossRef]
108. Kensek, K.M. Integration of Environmental Sensors with BIM: Case studies using Arduino. *Dynamo Revit API Inf. La Constr.* **2014**, *66*. [CrossRef]
109. Ness, D.; Swift, J.; Ranasinghe, D.C.; Xing, K.; Soebarto, V. Smart steel: New paradigms for the reuse of steel enabled by digital tracking and modelling. *J. Clean. Prod.* **2015**, *98*, 292–303. [CrossRef]
110. Zhao, W.; Liang, Y. Energy-Efficient and Robust In-Network Inference in Wireless Sensor Networks. *IEEE Trans. Cybern.* **2015**, *45*, 2105–2118. [CrossRef] [PubMed]
111. Habibi, S. Smart innovation systems for indoor environmental quality (IEQ). *J. Build. Eng.* **2016**, *8*, 1–13. [CrossRef]
112. Lee, D.; Cha, G.; Park, S. A study on data visualisation of embedded sensors for building energy monitoring using BIM. *Int. J. Precis. Eng. Manuf.* **2016**, *17*, 807–814. [CrossRef]
113. Habibi, S. Micro-climatization and real-time digitalisation effects on energy efficiency based on user behaviour. *Build. Environ.* **2017**, *114*, 410–428. [CrossRef]
114. McGlinn, K.; Yuce, B.; Wicaksono, H.; Howell, S.; Rezgui, Y. Usability evaluation of a web-based tool for supporting holistic building energy management. *Autom. Constr.* **2017**, *84*, 154–165. [CrossRef]
115. Dave, B.; Buda, A.; Nurminen, A.; Främling, K. A framework for integrating BIM and IoT through open standards. *Autom. Constr.* **2018**, *95*, 35–45. [CrossRef]

116. Francisco, A.; Truong, H.; Khosrowpour, A.; Taylor, J.E.; Mohammadi, N. Occupant perceptions of building information model-based energy visualisations in eco-feedback systems. *Appl. Energy.* **2018**, *221*, 220–228. [CrossRef]
117. Pasini, D. Connecting BIM and IoT for addressing user awareness toward energy savings. *J. Struct. Integr. Maint.* **2018**, *3*, 243–253. [CrossRef]
118. Kang, T. Bim-based human machine interface (Hmi) framework for energy management. *Sustainability* **2020**, *12*, 8861. [CrossRef]
119. Mataloto, B.; Mendes, H.; Ferreira, J.C. Things2people interaction toward energy savings in shared spaces using BIM. *Appl. Sci.* **2020**, *10*, 5709. [CrossRef]
120. Hirakraj, B.; Debasis, S.; Rajesh, G. Application of integrated fuzzy FCM-BIM-IoT for sustainable material selection and energy management of metro rail station box project in western India. *Innov. Infrastruct. Solut.* **2021**, *6*, 73. [CrossRef]
121. Sepasgozar, S.M.E.; Hui, F.K.P.; Shirowzhan, S.; Foroozanfar, M.; Yang, L.; Aye, L. Lean practices using building information modeling (Bim) and digital twinning for sustainable construction. *Sustainability* **2021**, *13*, 161. [CrossRef]
122. Tagliabue, L.C.; Cecconi, F.R.; Maltese, S.; Rinaldi, S.; Ciribini, A.L.C.; Flammini, A. Leveraging digital twin for sustainability assessment of an educational building. *Sustainability* **2021**, *13*, 480. [CrossRef]
123. Wang, X.; Love, P.E.D.; Kim, M.J.; Park, C.S.; Sing, C.P.; Hou, L. A conceptual framework for integrating building information modeling with augmented reality. *Autom. Constr.* **2013**, *34*, 37–44. [CrossRef]
124. Alves, M.; Carreira, P.; Costa, A.A. BIMSL: A generic approach to the integration of building information models with real-time sensor data. *Autom. Constr.* **2017**, *84*, 304–314. [CrossRef]
125. Edmondson, V.; Cerny, M.; Lim, M.; Gledson, B.; Lockley, S.; Woodward, J. A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management. *Autom. Constr.* **2018**, *91*, 193–205. [CrossRef]
126. Kang, K.; Lin, J.; Zhang, J. BIM- and IoT-based monitoring framework for building performance management. *J. Struct. Integr. Maint.* **2018**, *3*, 254–261. [CrossRef]
127. El Ammari, K.; Hammad, A. Remote interactive collaboration in facilities management using BIM-based mixed reality. *Autom. Constr.* **2019**, *107*, 102940. [CrossRef]
128. Kazado, D.; Kavgic, M.; Eskicioglu, R. Integrating Building Information Modeling (Bim) And Sensor Technology For Facility Management. *J. Inf. Technol. Constr.* **2019**, *24*, 441. Available online: http://www.itcon.org/2019/23 (accessed on 20 February 2021).
129. Rashid, K.M.; Louis, J.; Fiawoyife, K.K. Wireless electric appliance control for smart buildings using indoor location tracking and BIM-based virtual environments. *Autom. Constr.* **2019**, *101*, 48–58. [CrossRef]
130. Rogage, K.; Clear, A.; Alwan, Z.; Lawrence, T.; Kelly, G. Assessing building performance in residential buildings using BIM and sensor data. *Int. J. Build. Pathol. Adapt.* **2019**, *38*, 176–191. [CrossRef]
131. Saar, C.C.; Klufallah, M.; Kuppusamy, S.; Yusof, A.; Shien, L.C.; Han, W.S. Bim integration in augmented reality model. *Int. J. Technol.* **2019**, *10*, 1266–1275. [CrossRef]
132. Tsai, Y.-H.; Wang, J.; Chien, W.-T.; Wei, C.-Y.; Wang, X.; Hsieh, S.-H. A BIM-based approach for predicting corrosion under insulation. *Autom. Constr.* **2019**, *107*, 102923. [CrossRef]
133. Zhai, Y.; Chen, K.; Zhou, J.X.; Cao, J.; Lyu, Z.; Jin, X.; Shen, G.Q.P.; Lu, W.; Huang, G.Q. An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong. *Adv. Eng. Inform.* **2019**, *42*, 100997. [CrossRef]
134. Edirisinghe, R.; Woo, J. BIM-based performance monitoring for smart building management. *Facilities* **2020**, *39*, 19–35. [CrossRef]
135. Pavón, R.M.; Alvarez, A.A.A.; Alberti, M.G. BIM-based educational and facility management of large university venues. *Appl. Sci.* **2020**, *10*, 7976. [CrossRef]
136. Quinn, C.; Shabestari, A.Z.; Misic, T.; Gilani, S.; Litoiu, M.; McArthur, J.J. Building automation system—BIM integration using a linked data structure. *Autom. Constr.* **2020**, *118*, 103257. [CrossRef]
137. Valinejadshoubi, M.; Moselhi, O.; Bagchi, A. Integrating BIM into sensor-based facilities management operations. *J. Facil. Manag.* **2021**. Ahead of Print. [CrossRef]
138. Zhang, Y.Y.; Kang, K.; Lin, J.R.; Zhang, J.P.; Zhang, Y. Building information modeling–based cyber-physical platform for building performance monitoring. *Int. J. Distrib. Sens. Netw.* **2020**, *16*, 2020. [CrossRef]
139. Gao, X.; Pishdad-Bozorgi, P.; Shelden, D.R.; Tang, S. Internet of Things Enabled Data Acquisition Framework for Smart Building Applications. *J. Constr. Eng. Manag.* **2021**, *147*, 04020169. [CrossRef]
140. Štefanič, M.; Stankovski, V. A review of technologies and applications for smart construction. *Proc. Inst. Civ. Eng. Civ. Eng.* **2018**, *172*, 83–87. [CrossRef]
141. 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. *Autom. Constr.* **2019**, *101*, 127–139. [CrossRef]
142. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, 103179. [CrossRef]
143. Panteli, C.; Kylili, A.; Fokaides, P.A. Building information modelling applications in smart buildings: From design to commissioning and beyond A critical review. *J. Clean. Prod.* **2020**, *265*. [CrossRef]
144. Hou, L.; Wu, S.; Zhang, G.K.; Tan, Y.; Wang, X. Literature review of digital twins applications in constructionworkforce safety. *Appl. Sci.* **2021**, *11*, 339. [CrossRef]