Trends in BIM and IoT for Reactive Maintenance

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Abstract

It is widely acknowledged in the literature that a buildings' operational phase is directly related to the success of the business it supports. Building operation demands continuous efforts to reduce waste and operational costs while also improving service delivery. Of particular importance is the management of the Reactive Maintenance (RM) that if not managed efficiently can directly impact production lines and building user experiences, interrupting work and service provision. Building Information Modelling (BIM) and Internet of Things (IoT) solutions and devices have demonstrably delivered efficiency gains for some Facilities Management (FM) activities such as workplace management, building energy performance and post-occupancy evaluation. However, other areas, such as RM remain relatively unexplored. This research aims to identify BIM and IoT solutions applied to FM and propose a framework of BIM IoT uses assessed against associated gains, losses, enablers and barriers to implementation. A Systematic Literature Review (SLR) of journal and conference articles published between 2013 and 2018 was carried out to identify the outputs of BIM and IoT implementation for RM services. The review shows that the number of relevant articles is increasing and that there is also a lack of clarity regarding the cost-benefit of IoT. While the benefits and gains of systems are emphasized, disadvantages must be investigated. This research also revealed that there is a significant amount of uncertainty regarding guidance for the adoption of combined BIM and IoT applied to the improvement of RM services provision.

Keywords: Building Information Modelling (BIM), Internet of Things (IoT), Facilities Management (FM), Reactive Maintenance (RM)

1. Introduction

We crave efficiency in our businesses and yet fail to pay attention to the many areas that enable increased efficiency such as FM. Buildings can be too hot, too cold, too damp, or have high levels of CO2 concentration impacting staff performance. Poor maintenance can prevent the use of built assets, thus, driving staff out of offices, requiring clients to be relocated, and cancelling planned operations. The cost of fixing building problems is often a compounded of construction costs, reputational damages, service penalties and litigation costs. Firms also pay the price for not looking after facilities adequately, for not reacting quickly enough, and for not preventing problems before they occur. Although the desired alignment between business and FM has been continuously evolving as a reflection of improving information technology and communication systems effectiveness, there is still much to do. Early research such as Abel et al. (2006) and Atkin & Brooks (2009) showed that information modelling enables the coordination of FM processes that are essential for business operations while providing crucial information to facilities managers and corporate decision makers.

Building Information Modelling (BIM) is increasingly being investigated as a solution for increased efficiency in FM provision (e.g. Hosseini et al., 2018; Pärn, Edwards, & Sing, 2017; Patacas et al., 2016; Pin, Medina & MCarthur, 2018; Volk, Stengel, & Schultmann, 2014). There is evidence that information modelling is a powerful approach to aid facilities managers to improve building performance, to manage hard and soft operations more efficiently throughout the life cycle of buildings, and to enable circular economies. The amount of information about the real use of BIM for building operation and maintenance is growing with large public owners finally embracing and benefiting from BIM. However, much still needs to be understood. Advancements in areas such as IoT and Machine Learning has increased the number of potential uses of BIM in FM as well as the levels of efficiency that are possible to be achieved. Thus, a Systematic Literature Review (SLR) was carried out to aiming to gather and structure state-of-the-art knowledge about BIM and IoT implementation as an aid to FM. Special attention was paid to BIM and IoT for reactive maintenance (RM). From the analysis, a framework for the classification of research is proposed that identifies: research fields, FM priority areas, strategic FM operations and the benefits of and barriers to adoption. This framework should enable the establishment of a business case for BIM and IoT adoption.

2. Material and Methods

A SLR was carried out following the guidelines suggested by Gough et al. (2012). SLR generates subject context through the systematic identification, compilation, analysis and synthesis of reliable studies (Gough et al., 2012). It also ensures bias exemption (or, at least, its minimization) and increases the replicability of reviews (Morandi & Camargo, 2015). Also, it helps with establishing a picture of the transformations of a subject over a studied period while supporting decisions on future research paths and the use of research knowledge in practice. In this research, a research protocol was devised that led to the development of a conceptual framework used for data analysis. The SLR was divided into four steps, including research protocol development, searching, selection and extraction; as explained in the following sections.

3. Review Steps and findings

3.1 Systematic Review Entries

Table 1 provides an overview of the input criteria utilised as a part of the research protocol. Of twelve databases considered initially, seven were selected due to the availability of publications in the field of BIM and FM. Keywords and relevant Boolean Operators are presented in Table 1. The term “reactive maintenance” (RM) was excluded, so to broaden the search scope and to avoid the exclusion of relevant articles that use different terminology when referring to RM. Both peer-reviewed journal and conference articles were considered eligible publications. The research focused on recent innovative solutions; thus, only articles published between 2013 and 2018 were included.

Table 1: Research protocol

Item	Content
Research questions	What are the BIM and IoT solutions and devices recently applied to FM? In which areas and activities have these solutions been used? What are the main benefits, gains, enablers and barriers of this implementation?
Key objectives	To establish contextual knowledge regarding the implementation of BIM and IoT solutions on FM through the search, analysis and classification of articles and conference articles published between 2013 and 2018.
Databases	1. Scopus, 2. Technology Collection (ProQuest), 3. Science Direct (Elsevier), 4. Directory of Open Access Journals, 5. ASCE Library, 6. Compendex (Engineering Village) and 7. Web of Science (Web of Knowledge).
Keywords	("Building Information Modeling" OR "Building Information Modelling" OR BIM) ("Facilities Management" OR "Facility Management" OR FM) AND ("Internet of things" OR IoT)
Filters	Year of publication: 2013 to 2018. Type of publication: peer-reviewed journal and

	conference articles. Idiom: English, Portuguese, Spanish, Italian
Selection criteria	Inclusion criteria: articles investigating the implementation of BIM and IoT solutions in FM. Exclusion criteria: Publications that were not related to BIM and IoT for FM; outside the investigated research area; not written in the determined idioms.

In total, 273 publications were initially identified from journal articles, conference proceedings and PhD theses. After applying inclusion and exclusion criteria, 49 publications were selected for further analysis. Data was extracted through full-text review and publications classified according to title, authorship, type of publication, publication year, source (journal or conference), country, keywords, and three key areas: BIM and IoT solutions and devices, FM areas and activities, and positive and negative results obtained. Additional nine publications were excluded from the selection as they failed to meet protocol criteria. Figure 1 shows the distribution of publications per database throughout the different searching stages and the predominance of Scopus, Technology Collection, Science Direct and Compendex for the final 40 publications selected.

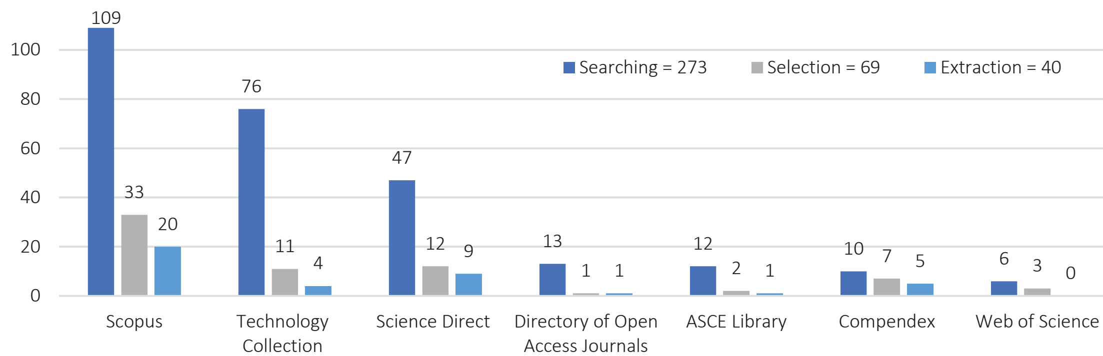
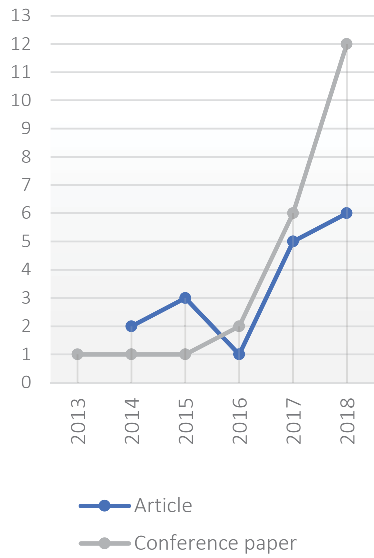


Fig. 1. Distribution of publications per database

3.2 General bibliometric analysis

The bibliometric analysis shows that 17 peer-reviewed journal articles and 23 conference articles were included and that there has been a steady increase in publications per year (Figure 2) since 2013. Figure 3 shows that contribution comes from 22 countries, thus revealing that although various countries started studying the subject, the critical mass is still embryonic (various countries with 1 or 2 publications). There is a predominance of articles (25) originated within, or with the participation of, European countries. The existence of bias is possible due to the use of English and Latin languages within the search. There is a concentration of publications in Italy (5), China (4), Taiwan (3) and the United Kingdom (3). Also, five articles spanned more than one country, evidencing a degree of international collaboration and knowledge sharing on this subject.

The distribution of publications according to where they were published shows 13 journals and 20 conferences. *Procedia Engineering, Advanced Engineering Informatics* and *Automation in Construction* have the highest concentration, accounting for approximately 47% of the articles (e.g. Costa et al., 2015; Kučera & Pitner, 2018), thus placing BIM and IoT for FM research within general engineering sources. No trend was identified for conferences, but there is a concentration of articles in events related to Automation and Robotics in Construction (5) (e.g. Chung et al., 2018; Lee et al., 2017) and IoT Technologies (3) (e.g. Pouke et al., 2018; and Ramprasad et al., 2018), which indicates that BIM and IoT for FM research refers to applied research.



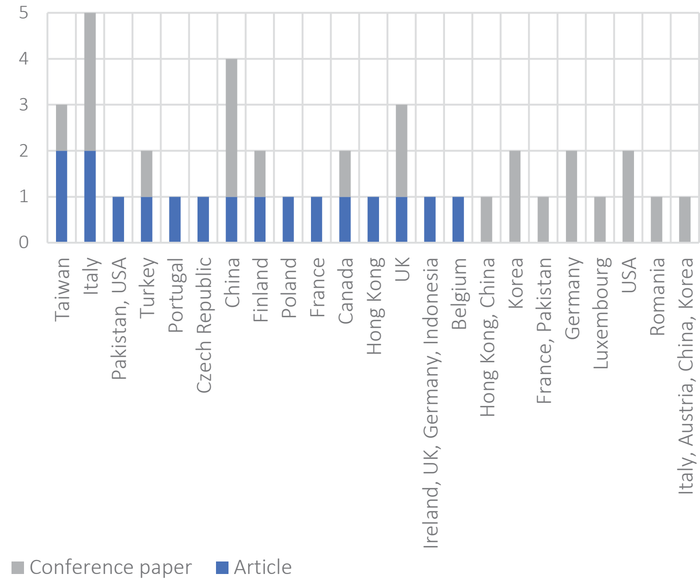


Fig. 2. Distributions of publications per year

Fig. 3. Distribution of publications per country

3.3 BIM and IoT core areas of research

With regards to core research areas, the analysed articles revealed three approaches being used for the integration of BIM and IoT for FM.

1) Process (17 entries) including the development of conceptual frameworks, methods and models for BIM-FM and IoT integration (e.g. Chen et al., 2015; Gokceli et al., 2017);

2) Technology (20 entries) including platform, software, system or tool for the integration of BIM and IoT technologies and interoperability of data related to FM (e.g. Arslan et al., 2017; Marroquin et al., 2018);

3) Theory (3 entries) including theory testing and theory generation for the integration of information and communications technology (ICT) or the description of previous applications of these technologies on BIM-FM and IoT (e.g. Araszkiewicz, 2017; Hanley & Brake, 2017).

Only articles that tested concepts through illustrative, prototype and pilot studies followed by real implementation were included in categories 1 and 2. Table 2 provides a summary of the results with examples to illustrate the three approaches. The following section covers the analysis of the 40 articles included, focusing on the technological aspects of BIM and IoT and its impact on FM and particularly on RM.

Table 2. FM BIM IoT Research core area, implementation and examples

Core area	Implementation	Example
1. Process: frameworks, methods and models for BIM and IoT integration	Illustrative, prototype or pilot implementation (9)	"A smart maintenance work process applicable to smart FM systems" (Chung et al., 2018)
	Real case implementation (6)	"A theoretical framework for digital systems integration of virtual models and smart technologies" (Mirarchi et al., 2018)
	No implementation (2)	"Realtime facility management system framework based on BIM and Web of Things" (Lee et al., 2013)

2. Technology: platforms, software, systems and tool for BIM and IoT integration	Illustrative, prototype or pilot implementation (14)	"BeDIPS - Building/environment Data-based Indoor Positioning System" (Liu et al., 2015)
	Real case implementation (6)	"3i buildings Systems - Intelligent, Interactive, and Immersive Buildings Systems" (Costa et al., 2015)
3. Theory	No implementation (3)	"Cup-of-Water theory" (Ye et al., 2018)

3.4 BIM and IoT solutions and devices for FM

With regards to IoT sensing devices, five key technologies are explicitly applied to FM activities independently or in combination. Out of 51 technologies mentioned, 73% are sensors and actuators (e.g. Dave et al., 2018; Gunduz et al., 2017), including, for example, Bluetooth Low Energy (BLE) beacons, general sensors for measuring temperature, humidity, CO2, lighting, occupancy and virtual sensors (added as an object within the 3D model of the facility); For RM, sensors are integrated into an indoor location system to identify users' position when reporting a failure (Mirarchi et al., 2018); 14% are Radio-frequency identification (RFID) tags and readers (e.g. Motamedi et al., 2016); 4% are smart cameras (e.g. Marroquin et al., 2018) and 4% are Quick Response (QR) codes used in RM for the acquisition and tracking of maintenance information (Lin et al., 2014). Finally, 5% of the articles were not sufficiently clear to fit within one of the above categories; one example is the "Smart field BIM-FM technology proposed by Chung et al. (2018) to support maintenance work on site.

Seven categories were proposed to classify solutions for BIM and the integration of data from sensing devices in FM: software application, system and network application; cloud and database solution; availability of building system; mobile application; smart devices; and associated technologies (Table 3). The results show a concentration of *Autodesk* software solutions, described in 19 publications, including 1 journal article describing the use of software for capturing and storing facility maintenance information to support RM, such as maintenance records and interface reports (Lin et al., 2014); other software solutions have been utilized less often, such as Unity software (3) and Trimble Tekla Structures (1). Building Management Systems (BMS) are present in 6 articles, followed by Building Automation Systems (BAS) in 4 publications. Nine articles applied user-friendly mobile applications, including the *Aalto Space, HereUAre* and *Nextome Noovle,* used in RM for end-users and FM staff registering and localising faults and monitoring service attendance (Mirarchi et al., 2018). Smartphones are mentioned in 10 publications within the smart device category, followed by Arduino in 3 publications. General smart devices are described in 5 articles, including webcam-enabled tablet and notebook supporting maintenance activities, such as fault location via QR code reading, visualisation of records information, monitoring service status and generation of reports (Lin et al., 2014).

Other FM associated technologies found include Blockchain for data security; Machine learning for automation of energy consumption data collection, processing and generation; photogrammetry and laser scanning associated with Geographic Information System (GIS) and Global Positioning System (GPS) for data digitalisation. Particularly applied to RM were Virtual Reality (VR) and Augmented Reality (AR) support site positioning and the visualisation of real-time facility information during maintenance inspections (Chung et al., 2018).

Table 3. FM BIM and IoT solutions

Item	Main BIM and IoT solutions and examples of publications
Software	Autodesk software (Revit, Revit Architecture, Dynamo, Green Building Studio, 3D Max, Autocad) (e.g. Lin et al. (2014); Unity Game Engine (e.g. Louis & Rashid, 2018); Trimble Tekla Structures (Costin et al., 2014)
System	Wireless Sensor Networks (WSN) (e.g. Ph.D & Ye, 2018); Integrated

and network	Workplace Management System (IWMS) (e.g. Hanley & Brake, 2017); IoT Watson IBM (Ciribini et al., 2017); Near-field communications (NFC) (Araszkiewicz, 2017)
Cloud and database	Microsoft SQL Server (Gerrish, Ruikar, Cook, Johnson, & Philip, 2018), IoT Platform Azure (Teizer et al., 2017), MS Access database (Costin et al., 2014)
Building system	Building Management System (BMS) (Gokceli et al., 2017), Building Automation System (BAS) (Kučera & Pitner, 2018)
Mobile application	Aalto Space mobile application (Dave et al., 2018; Kubler et al., 2016), HereUAre (Liu et al., 2015), Nextome Noovle mobile apps (Mirarchi et al., 2018)
Smart devices	Smartphone (e.g. Vandecasteele et al., 2017), Arduino (e.g. Chang et al., 2018), Tablet and Notebook (e.g. Lin et al., 2014), Wearable devices (e.g. Desogus et al., 2017)
Associated Technologies	Blockchain (Ye et al., 2018), Virtual Reality (VR) and Augmented Reality (AR) (Chung et al., 2018), Machine learning (McGlinn et al., 2017), Aerial photogrammetry (Edmondson et al., 2018), Geographic Information System (GIS) (Ronzino et al., 2015), Global Positioning System (GPS) (Ph.D & Ye, 2018)

3.5 FM areas, activities and applications

Figure 4 presents the classification and occurrence of the publications according to the FM areas and activities as described by Barrett and Finch (2014). Because some publications combined more than one area and activity, the total number of occurrences is higher than the number of analysed articles. Building operations and maintenance is the most investigated FM area with 84 entries, followed by general/office services (12) and facility planning (10). With regards to FM activities, the five most relevant are: Monitoring performance (26), running and maintaining plant (18), voice and data communication (16), health and safety (12) and energy management (14) where emphasis has been placed upon predictive actions related to energy consumption optimisation rather than corrective ones.

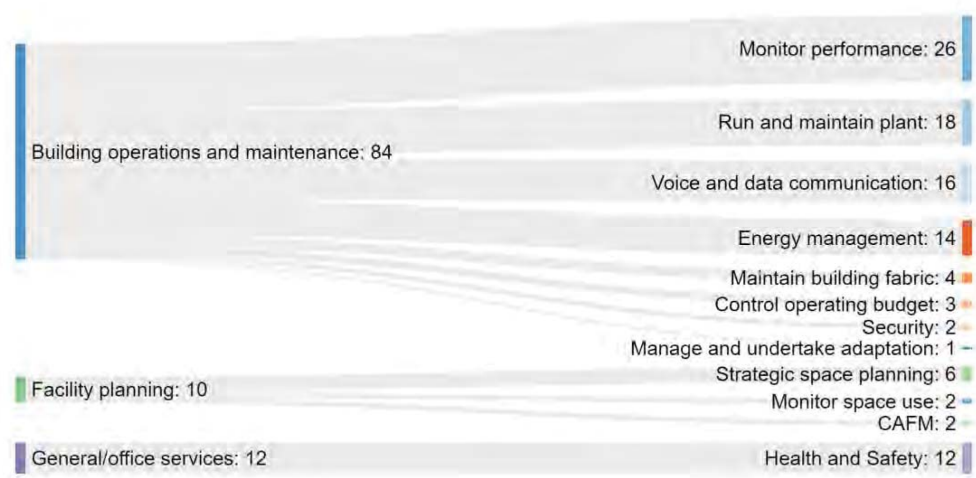


Fig. 4. Classification and occurrence of FM areas and activities

Key applications and examples found are summarised in Figure 5. These include building data management and synchronization (9) (e.g. Ramprasad et al., 2018), environmental monitoring and compliance checking (7) (e.g. Terkaj et al., 2017), energy and environmental management, monitoring and visualization (5) (e.g. Chang et al., 2018), operational and maintenance management (4) (e.g. Desogus et al., 2017) and location tracking (3) (e.g. Costin et al., 2014). Only three publications clearly describe applications relating to Maintenance Work as a process, from which two are related to Reactive Maintenance (correction, inspection and repair) (Lin et al., 2014; Mirarchi et al., 2018).

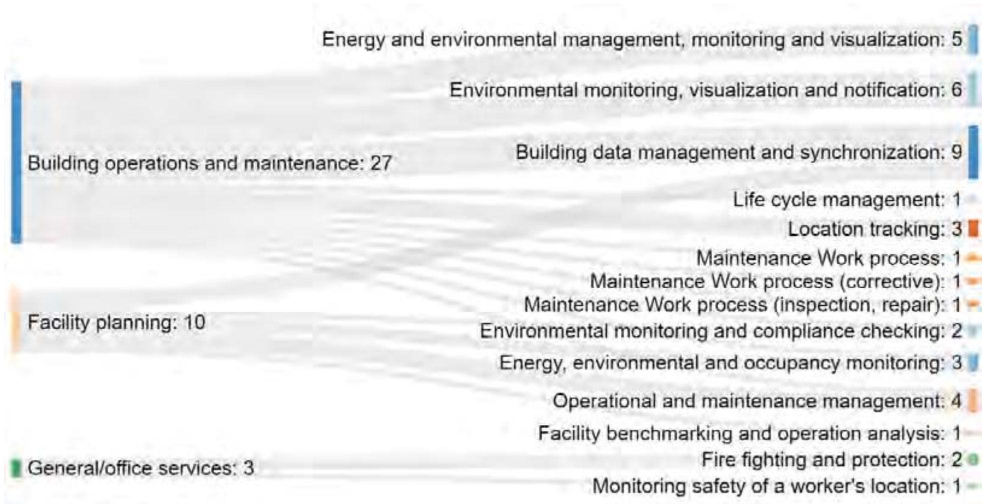


Fig. 5. Classification and occurrence of FM areas and applications of BIM and IoT

3.6 Outputs of BIM and IoT implementation for FM

Selected publications generated a total of 112 entries related to BIM and IoT implementation for FM according to its' measured and potential benefits (60), gains (32), enablers (5) and barriers (15). These were grouped into seven subcategories (Figure 6): increase or decrease of user's health & safety, comfort and satisfaction, technological issues, increase or decrease of FM efficiency, productivity and financial issues, occurrence of ethical and user privacy issues, increased or decreased environmental sustainability, enhanced (shared) building data management and asset planning, management and operation. No losses resulting from the adoption of BIM-FM and IoT were reported within the selected publications, thus revealing positive bias within the research. This aspect is depicted in Figure 6, showing that positive outputs are represented more often than negative ones. Readers must consider, however, that negative results tend not to be published due to risks associated with reputational damage as it occurs in POE studies.

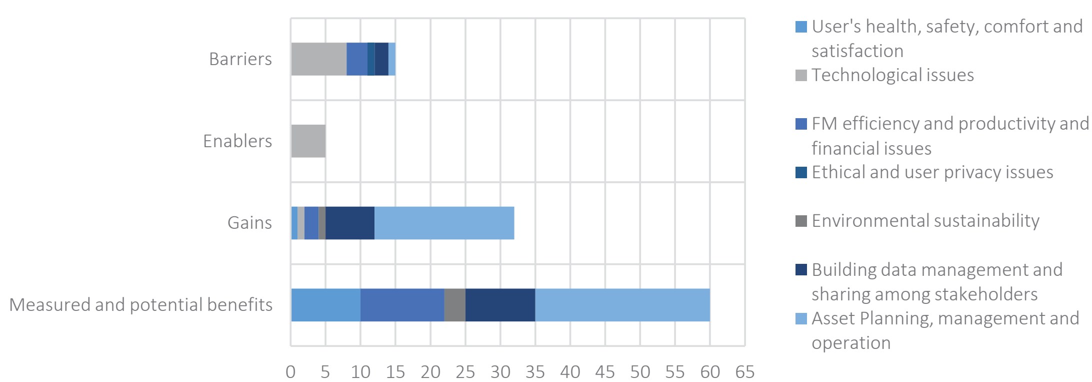


Fig. 6. Distribution of BIM and IoT implementation outputs for FM per publication

In relation to identified benefits, articles mostly describe the potential impact of the combined technologies on asset planning management and operations (25) followed by FM efficiency and productivity and financial issues (12). General examples within this category include "anticipating users' needs to support decision-making for retrofit projects" (Desogus et al., 2017); and "AEC/FM digitalisation high efficiency and security" (Ye et al., 2018), while for RM the benefits are "in facilitating FM updates and transfers in the BIM environment" (e.g. Lin et al., 2014) and "the management of the whole cycle of maintenance activities using a unique integrated system" (e.g. Mirarchi et al., 2018).

As expected, the main gains relate to asset planning, management and operation (20) and building data management and sharing (10). For example, instant information about problems supporting facilities managers in rapid fault detection (Desogus et al., 2017); availability of "a complete management system", including historical data and current condition, enabling verifications on the behaviour of buildings (Di Giuda et al., 2018). Technology is a key enabler for BIM and IoT implementation for FM in 5 entries. For RM, Lin et al. (2014) highlight the low cost of QR code labels in comparison to RFID technologies; Ciribini et al. (2017) explore machine learning and IoT. In their research, sensors generate real-time human activity data that informs adaptive and predictive strategies embedded in BMS systems which makes automatic changes in environmental controllers (e.g. light levels and temperature control) for improved users' comfort and service attendance. Technology is also seen as the core barrier for BIM and IoT based services (8), followed by FM efficiency and productivity and financial issues (3). Examples include: "trade-offs between interoperability problems within existing sensor systems and high costs related to the development of simplified and integrated systems" (e.g. Arslan et al., 2014); the "large volume of inaccessible and incoherent information gathered through sensors" (e.g. Desogus et al., 2017). For RM, examples include reported difficulties for new user to operate the BIM model in the BIFM system; the fragility of QR code labels to external environmental pollution (Lin et al., 2014); and the limited precision of location system (Mirarchi et al., 2018).

3.7 Conceptual framework of BIM IoT implementation for FMRM

The conceptual framework presented in Figure 7 synthesises the key aspects for the investigation of BIM and IoT implementation for FM/RM. The areas within the framework are the classification of FM areas and activities; definition of an approach for BIM and IoT integration; characterisation of the structure for combining BIM and IoT solutions and devices; and identification of the outputs of BIM and IoT implementation.

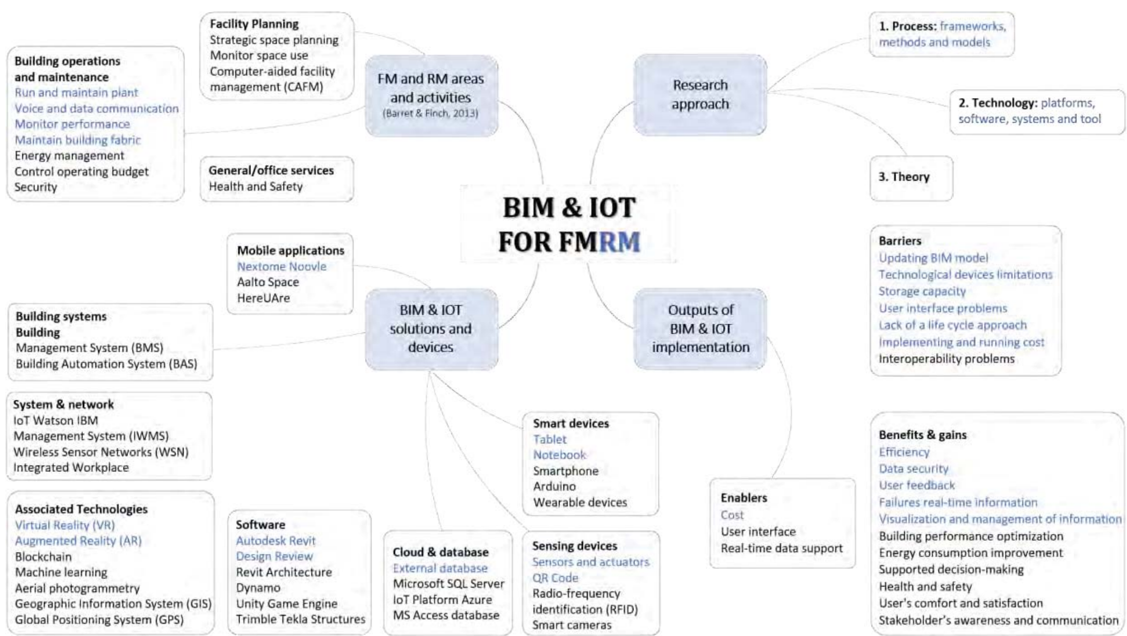


Fig. 7. Framework for BIM and IoT implementation for FMRM

4. Discussion

This work evidences the scarcity of studies in the field during the investigated period. The predominance of publications from European countries stored in three databases highlights the concentration of the topic in specific scientific environments. The prevalence of studies proposing conceptual processes and technological tools for BIM and IoT integration evidences the novelty of the theme and the need for advances in storing, exchanging and integrating building operation data, establishing a background for further implementation. Moreover, most of those constructs were validated through pilot implementations, highlighting, on one hand, the interest in developing applicable solutions, while on the other hand, illustrating the demand for implementations in real cases as a strategy for measuring tangible effects over the efficiency FM activities. As shown in Figure 3, although the publications were less representative between 2013 and 2016, we can observe an increasing trend after that, particularly in conference articles, which totalled twice the number of articles in 2018.

As summarised in Table 3, the solutions for building information modelling involve many components beyond sensing devices and software, which makes for even more complex BIM and IoT combined implementation. For FM activities, in general, there is a prevalence of sensors and RFID tags and readers, Autodesk software, smartphones, mobile applications and associated technologies (e.g. VR, AR). Although no trend is verified for RM in the small sample analysed, there is the potential for adapting general solutions to these activities, respecting inherent limitations highlighted by some authors (Chung et al., 2018; Lin et al., 2014; Mirarchi et al., 2018).

The predominance of publications about building operations and maintenance, particularly for monitoring building performance, managing energy consumption and voice and data communication shows that BIM and IoT based FM plays a key role in enhancing FM activities during the life cycle of a building. It provides intelligent data and solutions for enhancing the Operation and Maintenance (O&M) stage, and also to feedback and integrate designers and contractors in the early stages of the design process. However, the availability of only two RM related articles evidences the lack of studies in this area, disregarding its impact on service provision, user satisfaction and business value.

The measured and potential benefits and gains are the most significant outputs of BIM and IoT implementation for FM. In general, and for RM, the emphasis has been on the integration of building information in a centralized database, the availability of real-time updated information, the improvement of the quality and management of information among stakeholders, the fast response to faults and the performance of buildings over the lifespan. Technology is both the main enabler for BIM and IoT implementation due to its capability to process real-time information and to propose alternatives for improving user comfort and service attendance and as the main barrier as the cost and complexity of collecting, storing and exchanging interoperable building data are still major challenges. There is an evident bias towards technology-related research.

Regards to BIM/IoT/RM-based services, this article has identified different approaches to improve the communication and management of asset information. Mirarchi et al. (2018) develop a system for asset traceability, damage detection and reporting and communication of failures, based on indoor location technologies (i.e. GIS and mobile application), integrated to FM BIM models. The focus is on tracking users' position as one reference for locating the reported problems and linking this information to the BIM model. Although faults' precise location requires being interpreted by the facility manager according to other sources of information (e.g. photos, descriptions), the system provides an easy interface for users, FM staff and the supply chain actively participating in the RM process, improving the efficiency of the service. A mobile system for inspection and maintenance work was also proposed by Lin et al. (2014), integrating asset information captured through 2D barcode technology to FM BIM models. In their research, the emphasis was placed on FM staff acquiring and tracking asset information directly from the labelled elements of the building, improving the information sharing and the RM services efficiency. With distinct levels of end-user involvement, both solutions face the challenge to overcome the technological limitations and to structure the modelling, transference and update of information among IoT, FM and BIM systems, thus requiring further investigations.

Holistic approaches, covering not only the technical challenges in the FM process but also people issues and the changing business models driving FM, such as the circular economy and how we are now learning from information related to the whole life cycle of existing buildings in design of new buildings, did not appear in this systematic literature review. Although the positive outputs outweigh the negative ones, it is necessary to deeply investigate all the barriers and then propose strategies to mitigate their impact on BIM and IoT applications for FM, optimising the use of resources and seeking affordable devices and solutions for each situation. Also, it is essential to map RM processes in more detail in order to identify which services and activities can be potentially improved through BIM and IoT implementation. More research is needed to fill this gap.

5. Conclusion

Through an SLR, this work establishes a context for the implementation of BIM and IoT solutions in FM between 2013 and 2018. Addressing the research questions, BIM and IoT devices and solutions recently applied to FM, and particularly to RM, were identified, as well as the main FM areas, activities and applications. Finally, the outputs of this implementation were examined, highlighting benefits, gains and enablers rather than barriers and losses. The work indicates that RM activities represent a small field of investigation, providing a range of opportunities for new approaches and applications. The research shows that the number of articles is increasing and that there is a lack of clarity regarding the cost-benefit of BIM and IoT combined implementation. The categories and strategies for developing this work are summarised in the proposed conceptual framework which, along with the findings, contribute to understand the subject and to support future studies.

One of the limitations of this study was the difficulty of tracking publications within the databases due to the multidisciplinary nature of the subject, crossing engineering and computer science fields. Also, the focus on articles is based on secondary sources of data, providing a synthesis of previous investigations. In this respect, further research supported by empirical evidence (e.g. case studies, surveys, interviews) is recommended in order to provide metrics around costs and the impacts of BIM and IoT implementation for FM, particularly for RM. These and future studies are necessary to strengthening FM's key role in improving building life-cycle efficiency and the AEC industry.

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