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Review article

BIM-enabled facilities operation and maintenance: A review

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ABSTRACT

Building Information modeling (BIM) has the potential to advance and transform facilities Operation and Maintenance (O&M) by providing a platform for facility managers to retrieve, analyze, and process building information in a digitalized 3D environment. Currently, because of rapid developments in BIM, researchers and industry professionals need a state-of-the-art overview of BIM implementation and research in facility O&M. This paper presents a review of recent publications on the topic. It aims to evaluate and summarize the current BIM-O&M research and application developments from a facility manager's point of view, analyze research trends, and identify research gaps and promising future research directions. The scope of this research includes the academic articles, industry reports and guidelines pertaining to using BIM to improve selected facility O&M activities, including maintenance and repair, emergency management, energy management, change/relocation management, and security. The content analysis results show that research on BIM for O&M is still in its early stage and most of the current research has focused on energy management. We have identified that the interoperability in the BIM-O&M context is still a challenge and adopting the National Institute of Standards and Technology (NIST) Cyber-Physical Systems (CPS) Framework is a potential starting point to address this issue. More studies involving surveys are needed to understand the underlying O&M principles for BIM implementation – data requirements, areas of inefficiencies, the process changes. In addition, more studies on the return on investment of the innovative systems are required to justify the value of BIM-O&M applications and an improved Life Cycle Cost Analysis method is critical for such justifications.

1. Introduction

Building Information Modeling (BIM) is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle" [1,2]. The referred building information model is "the shared digital representation of physical and functional characteristics of any built object" [1,3,4]. In recent years, the proliferation of BIM[1] has provided designers and builders with new opportunities to achieve better quality buildings at lower cost and shorter project duration [1,5–7]. BIM technology has the potential to provide value to the owners and operators by offering them a powerful means to retrieve information from a virtual model of the facility [8]. However, even though the need for BIM in facility Operation and Maintenance (O&M) has been acknowledged since 2010 [4,9–12], facility operators have yet to embrace the benefits of BIM. In 2015, a survey in Netherland indicates that, even for the companies who have already implemented BIM in the design and construction phases, the added value of BIM in the facility operation phase is marginal [13]. The main reason for this low value realization is "a lack of alignment between people, processes, and systems, particularly in a manner that agrees with the basic principles of BIM" [13]. For a facility manager, given the BIM and the information contained, how to use them to support facility management (FM) activities is the question. Researchers and industry professionals need a state-of-the-art overview of BIM developments in facility O&M.

This research provides insights into current BIM capabilities in supporting facility O&M, by examining how each O&M activity can be leveraged by BIM and to what extent their efficiency and effectiveness can be improved. It aims to evaluate and summarize current BIM-O&M developments, analyze research and application trends, and identify research gaps and promising future research directions.

The scope of this research includes the academic articles, industry

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[1] Because "Building Information Modeling" and "Building Information Model" are often used interchangeably [1], in this paper, the abbreviation "BIM" is used to represent both the Building Information Modeling (the related process and technology) and the Building Information Model (the digital representation of built objects).

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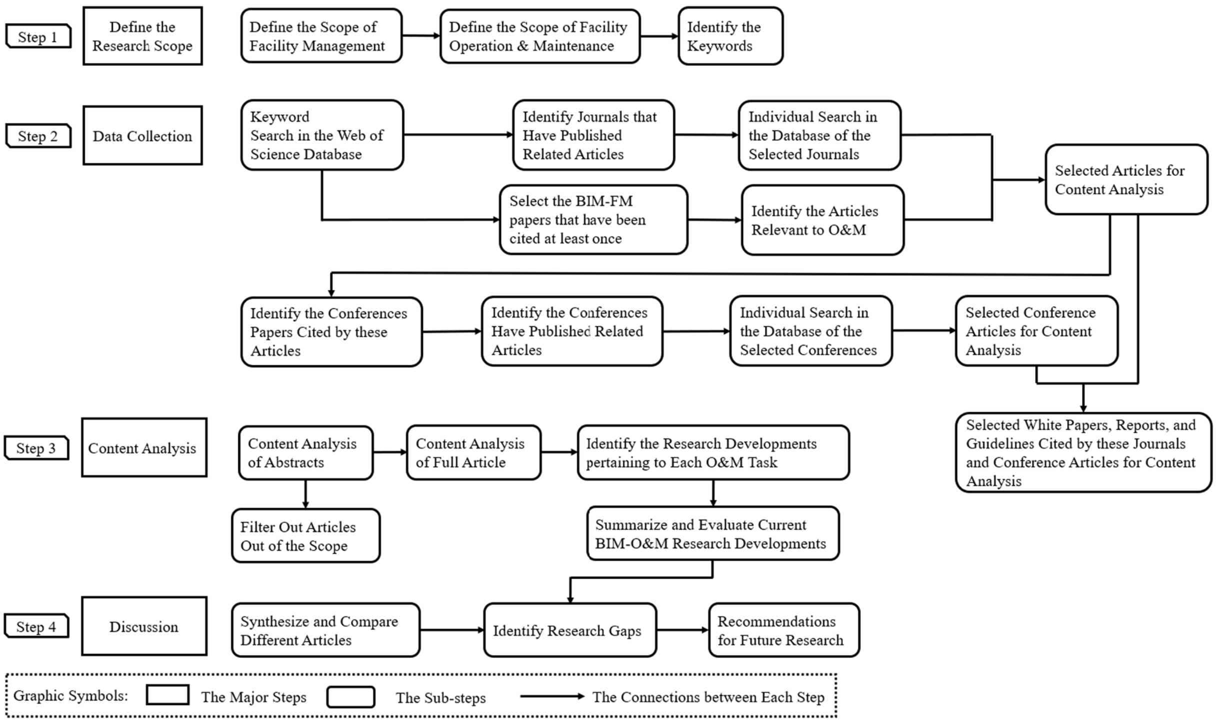


Fig. 1. Research methods and procedure of this study.

reports and guidelines pertaining to BIM applications in improving facility O&M activities, including maintenance and repair, energy management, emergency management, change/relocation management, and security. This research excludes publications pertaining to infrastructure, the survey of existing buildings, BIM creation and assessment, refurbishment, retrofit, and deconstruction. The technology achievements, innovative processes, and research gaps are discussed in detail and analyzed from a facility manager's point of view. An overview of BIM-enabled toolsets and practices is provided for researchers and practitioners interested in the BIM-FM field.

2. Methodology

This paper involves a literature review on both academic and applied publications that focus on BIM applications in O&M activities. The review process, which is inspired by [14], consists of four main steps (Fig. 1): (1) defining the research scope and identifying the keywords used for searching in the database; (2) collecting the articles that are within the scope of this review; (3) content analysis and identify the research developments presented in the articles as they relate to each O &M tasks; the current developments in the BIM-O&M field are summarized and evaluated in Section 3. (4) discussing the identified research gaps and recommendations for future research, which is presented in Section 4.

To collect the articles, we first conducted a keyword search in the *Web of Science* database to identify the journals and conferences that have published related articles. We only consider the conference papers published in the proceedings that have been cited by the identified journal papers to set a threshold for the paper quality. After these journals and conference proceedings are identified, individual searches were conducted in their databases to collect the articles to review. We also searched the BIM-FM articles that have been cited at least once on the *Web of Science* and identified the ones pertinent to O&M. In addition, the white papers, reports, and guidelines that are cited by all the identified journal and conference articles are also selected for content analysis. The ones pertaining to our topic are also included in this review.

Fig. 1 illustrates the research methods and procedure of this study.

2.1. Define the research scope

FM is "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology" [15]. It involves "the approach, analysis, and optimization of all processes, relating to the building or other real estates that can be used for business needs of the organization, except the core-business of the organization" [16]. FM can be viewed from a narrow and a broader perspective. Many publications refer to FM in its narrow sense, which basically equals to facility operation and maintenance. Intuitively, a facility manger's major job is to keep the building operating and to ensure all the equipment and systems function properly. However, the work scope of facility managers is much broader than just operation and maintenance. FM is a broad concept that includes a range of functions, although the definition of FM has evolved over time [17] and the required FM functions vary depending on the organization type. In this research, the classifications of FM activities are based on [16,18–27]. The common functions of FM are shown in Fig. 2. In some cases, facilities management is not limited to a single or a set of buildings of an organization but may concern the management of a whole city's facilities (urban facility management) [28]. In this study, the discussion of FM is limited to one or multiple facilities owned by one organization.

Facility Operation & Maintenance (O&M) "encompasses a broad spectrum of services, competencies, processes, and tools required to assure the built environment will perform the functions for which a facility was designed and constructed" [27]. As one of the major functions of FM, it typically includes the activities necessary for the building, its systems and equipment, and occupants to perform their intended function [27]. These activities are summarized in Fig. 2, based on [16,18–27]. In this research, articles with abstracts containing either "Building Information Modeling" or "BIM" combined with any of the identified O&M keywords, such as "operation & maintenance", "emergency management", and "energy management", are studied. We consider the research developments all over the world. The overview of current research and application developments in these areas are demonstrated and discussed in Section 3.

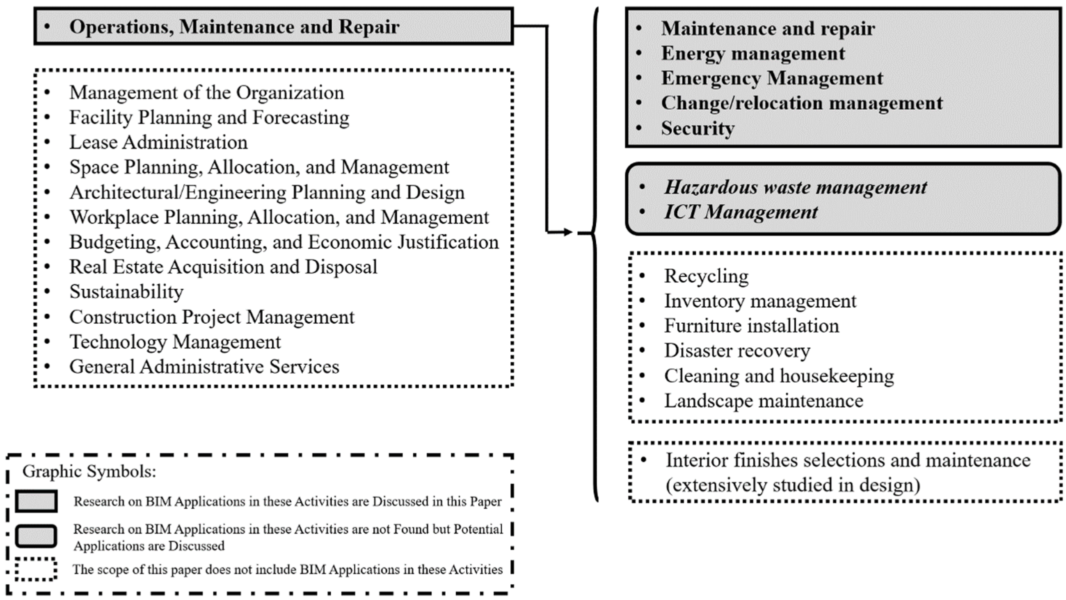


Fig. 2. Facility management and operation & maintenance activities [16,18–27] and the scope of this research on BIM applications for FM.

This study could not find any publication discussing BIM applications in the following O&M activities: hazardous waste management, Information and Communications Technology (ICT) asset management, furniture installation, disaster recovery, cleaning and housekeeping, and landscape maintenance. We speculate that research in these areas are scarce because these tasks can be accomplished satisfactorily with current practices and the add-value of BIM is limited in these areas. Further discussions and recommendations for future research on BIM applications in hazardous waste management, ICT asset management, and other research areas, are provided in Section 4.

2.2. Literature search and content analysis of abstracts

The academic publication selection process of this study draws on the methodology adopted in other review articles, such as [14,29]. In the preliminary search, we used "BIM" and "Building Information Modeling" combining with the O&M keywords to search through the *Web of Science (WoS)* database and identified 357 scientific articles, which are written in English and from the engineering and computer related fields. As [14] pointed out, Web of Science can only search the keywords in the title/abstract/keywords of the articles. Considering this, we also used the selected journals' and conferences' databases to conduct a thorough keyword search in the full article to make sure no article within our research scope is overlooked. These databases involve ELSEVIER, EMERALD, EBSCO, WILEY, ASCE, CIB, SPRINGER, T&F, ISPRS, IEEE Xplore, ACM Digital Library, etc. As a result, 448 more articles were included. In addition, to avoid omitting any influencing articles in this field, we also conducted a search in the WoS to identify the articles that have been cited at least once by other articles in the BIM-FM literature and identified the ones pertinent to O&M. 19 more articles were identified in this step.

Among the 824 articles identified by keyword search from the WoS database and the journals' and conferences' databases, after we filter out the articles outside of our research scope through a content analysis of the abstracts, there were 291 academic articles – 177 journal papers and 114 conference papers/book chapters – pertinent to BIM applications on O&M. In addition, we also included 19 reports and guidelines from the industry. We are cautious with the selection criteria for these industry articles because they have not been peer-reviewed and the credibility may be questionable. For example, a technical report conducted by a software company may oversell the functionality of its product. Hence, we only examine the industry articles that have been cited by identified journal and conference papers in the scope of this paper. We also distinguished journal papers and conference papers/book chapters because most of the research findings presented in journal papers have been examined through rigorous peer reviews, while many conference papers and book chapters demonstrate only preliminary results and hypothetical frameworks that may have not been validated.

2.3. Content analysis of the full article

In this step, the 291 identified articles pertinent to facility O&M were rigorously reviewed. Each reviewed paper is examined in the following aspects: (1) the research method, (2) applicable facility type, (3) whether an innovative system, a framework, or an approach is proposed, (4) whether a case study or a simulation is presented, (5) other technologies integrated (such as, Virtual Reality, Geographic Information System, etc.), (6) whether challenges and obstacles are discussed, and (7) whether a new O&M process is discussed. See Fig. 3 for the distribution of the reviewed journal articles on these aspects. In addition, the papers are also analyzed from the standpoint of which O&M activity they facilitate by the research developments and how. The results are discussed in detail in Section 3.

Within the 150 BIM-O&M journal papers (excluding the 27 literature reviews that, more or less, discussed BIM for FM), 70% of the publications propose an innovative system, framework or approach; 62% of them use case studies or experiments to validate the proposed system/framework/approach; 27% of them include contents regarding integrating BIM with other technologies, such as Augmented Reality (AT), Radio-frequency Identification (RFID), Geographic Information System (GIS), etc.

Through the review process, we identified three main research gaps of existing BIM-O&M studies, which are interoperability in the O&M context, understanding the underlying O&M principles for BIM implementation, return on investment. These research gaps and recommended solutions, together with three additional recommendations for future research – the potential BIM application in hazardous waste management, ICT asset management, and user-centered O&M systems – are discussed in Section 4.

2.4. Originality

Among the identified 27 literature reviews that mentioned BIM for

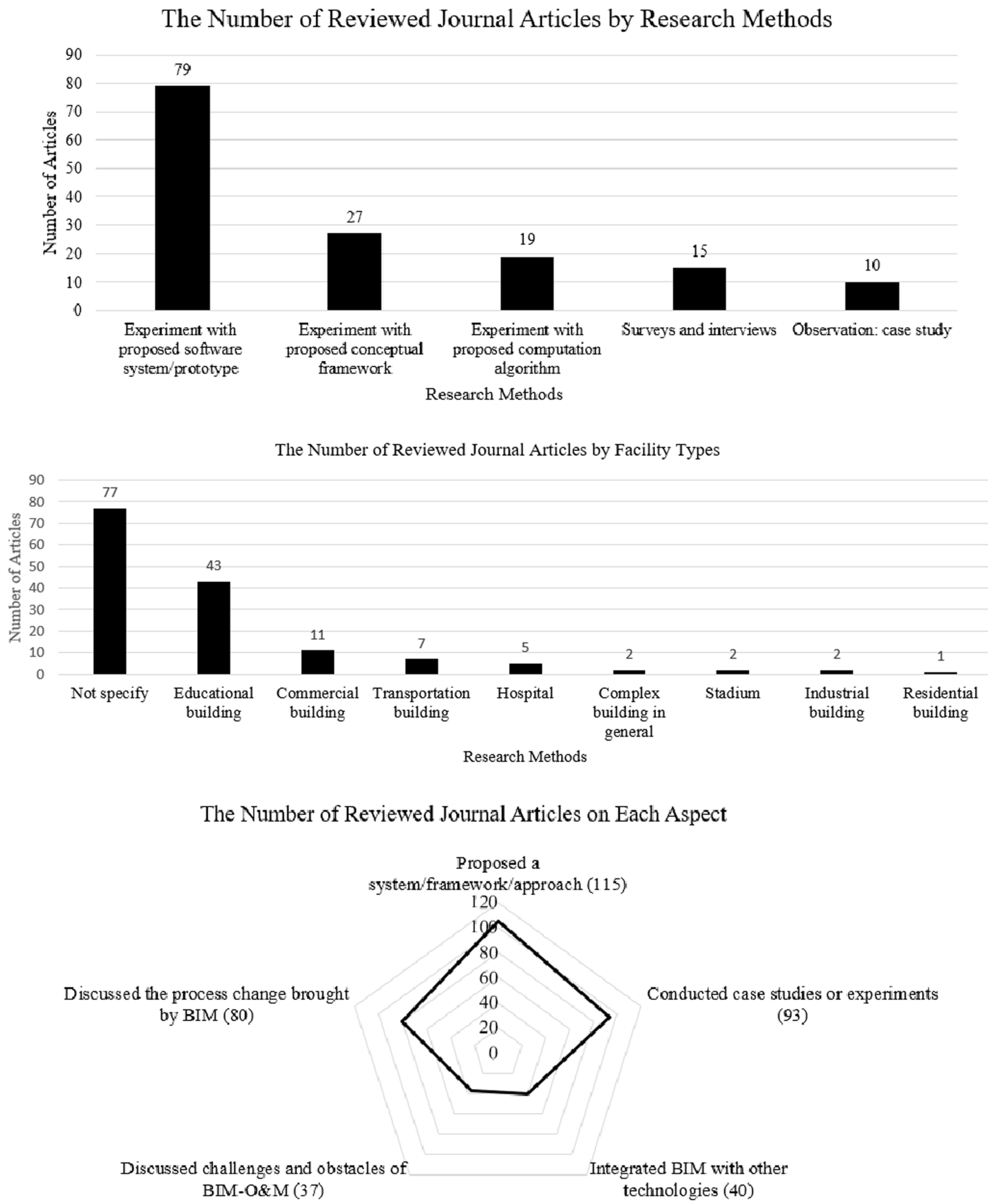


Fig. 3. Distribution of the reviewed journal articles on each aspect.

FM, 20 of them have different focuses rather than FM, including BIM for sustainability [29–32] and energy efficiency [33], BIM for the infrastructure industry [34,35], information technology and safety [36,37], system integration and interoperability [38], BIM and GIS integration [39–41], creating as-built BIMs [42], BIM protocols, guides and standards [43], BIM applications in tunnel engineering [44], and scientometric analysis of BIM research trends [14,45–48]. These papers only used one or two paragraphs to discuss BIM applications in FM. The other seven literature reviews involve generally discussing BIM applications in FM [17,49–52], BIM for existing buildings [4], and BIM for refurbishment and maintenance [12], which are summarized in Table 1.

As shown in Table 1, most of these literature reviews regard FM as one general function rather than distinguish specific FM activities in their discussions on BIM applications. FM is a broad concept that includes a range of functions (Fig. 2). Building operators and managers are dealing with numerous challenges in different types of FM tasks. The discussion pertaining to the BIM-FM implementations should be based on a clearly defined FM scope – which functions are being discussed – otherwise, the discussions would appear over-general and ambiguous.

Facility operation & maintenance (O&M) is just one of the FM functions, which also includes multiple activities, such as maintenance and repair, emergency management, energy management (Fig. 2). To our knowledge, there is no comprehensive overview that specifically focuses on recent research of BIM for facility O&M. We try to close this gap with the present paper. With a more focused scope, this research is an investigation of BIM developments and applications in the facility O

Table 1
Literature reviews on BIM for FM.

Article	Research Scope	Findings	Suggested future work	FM functions discussed	O&M activities discussed
Volk et al. [4]	The BIM creation, implementation, and research in existing buildings	(1) implementation of BIM in existing buildings is limited, (2) increasing maintenance functionalities in preexisting BIM are developing for recently constructed buildings, (3) applications and research approaches for deconstruction functionalities in BIM remain rare, (4) owners, facility managers, deconstructors and related consultants are hardly involved in BIM functionality development	(1) research on the worldwide spreading of BIM and related changes of processes and regulations (2) a comprehensive cost-benefit analysis of BIM implementation for existing buildings	Focusing on maintenance and deconstruction	Maintenance
Kassem et al. [50]	The value of BIM for FM	BIM can facilitate FM activities by improving the information handover, the accuracy and accessibility of FM data, and efficiency in work order execution	None	FM is discussed in general. No specific function is discussed separately	None
Ilter & Ergen [12]	BIM for building refurbishment and maintenance	Identified the dominant research topics: (1) building survey and as-built BIM, (2) modelling and managing energy, (3) design assessment, (4) access to and integration of maintenance information and knowledge, (5) information exchange and interoperability	(1) automation of as-built model creation through 3D laser scanning data (2) decision-making tool integrated with BIM-based energy simulation (3) interoperability (4) the paradigm shift among different stakeholders	Focusing on refurbishment and maintenance	Maintenance
Pärn et al. [17]	BIM for FM in general	Identified the need for: (1) long-term strategic aspirations (2) amelioration of data interoperability (3) augmented knowledge management (4) enhanced performance measurement (5) enriched training	(1) case studies on current practice and development (2) supplementary research on BIM-FM for asset management	FM is discussed in general. No specific function is discussed separately.	None
Edirisinghe et al. [49]	BIM for FM in general	Identified major aspects of BIM for FM by innovation diffusion theory. Proposed a framework that informs facility managers and the BIM-enabled FM implementation process	(1) specific FM applications and productivity gains (2) advanced applications in FM (3) regulations and BIM adoption	FM is discussed in general. No specific function is discussed separately	None
Naghshbandi [52]	BIM for FM in general	Identified the need for: (1) case studies and hard evidence to prove the benefit of BIM for FM, and clarify practical challenges (2) enhancing the relationship and advancing collaboration among different stakeholders	None	FM is discussed in general. No specific function is discussed separately	None
Miettinen et al. [51]	BIM for FM in general	(1) Literature of BIM implementation tends to omit the analysis of the existing FM systems (2) the demand for BIM-enabled FM has not been justified by well-articulated problems or developmental contradictions	None	FM is discussed in general. Maintenance is specifically mentioned.	Maintenance

&M field. From a facility manager's perspective, it provides a close look at the current BIM-O&M developments, research and application trends, identifies research gaps and promising future research directions, and provides recommendations to address the prevailing issues – interoperability, understanding the underlying O&M principle, and return on investment.

3. Overview of existing publications on BIM in facility O&M

In the past decade, there has been a growing trend of BIM-O&M publications. Among the 177 identified journal papers, except for 27 literature reviews of BIM and 55 papers that generally discuss BIM for facility O&M, 95 papers have explicit research goals that involve utilizing BIM to improve the efficiency and effectiveness of one or multiple O&M activities.

Based on the content analysis, the articles were grouped into six categories according to the O&M activities that can be improved by the research developments discussed in the articles: (1) maintenance and repair, (2) energy management, (3) emergency management, (4) change/relocation management, (5) security, and (6) facility O&M in general. These articles are comparatively analyzed in this section.

Fig. 4 shows the number of journal publications regarding BIM applications in each O&M activity type. It indicates that O&M activities, such as energy management, emergency management, and maintenance & repair have been studied relatively more by researchers as they found these activities to benefit more from BIM. Academic publications on BIM for security and change/relocation management are relatively scarce. The research findings pertaining to BIM applications on each of these O&M activities are discussed in this section.

3.1. Maintenance and repair

Facility maintenance refers to “the work necessary to maintain the originally anticipated useful life of a fixed asset”, which is preventive and proactive, while facility repair refers to “the work necessary to restore damaged or worn-out property to a normal operating condition”, which is curative and reactive [18]. By providing the three-dimensional (3D) -visualization-based information in an integrated form, BIM enables facility managers and technicians to locate building components more efficiently and reduces the effort to comprehend the displayed information [53]. The major research developments of BIM applications in facility maintenance and repair are summarized in Table 2. Four critical research emphases in this area are discussed in detail, which are understanding the current practice and information source, data exchange and system integration, data accessibility, and fault detection and diagnosis.

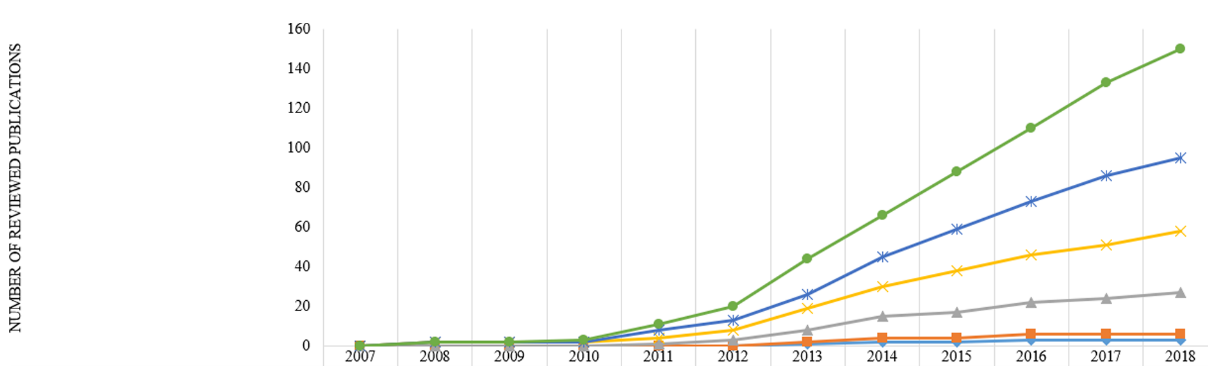
The most common problem facility managers face is the information accessibility issues [67]. During the facility operation phase, they usually do not have easy and quick access to the needed information to process work orders. To address this issue, BIM is used to integrate the fragmented FM information that is housed within different building management systems and to provide an intuitive information access interface.

3.1.1. Understanding the current practice and information source

The sources of required information for facility maintenance and repair involve the existing FM documentation in the archive, FM personnel's experience, and building management systems [55,65,68–70]. These systems include Building Automation System (BAS) [65,70,71], Computerized Maintenance Management Information System (CMMS) [62,65,72,73], Building Energy Management Systems (BEMS) [65], Electrical Instrumentation and Control (EIC) system [68], and Geographic Information system (GIS) [56,69,74,75]. Most of the reviewed articles in this filed discussed how to extract O&M related information from these building systems. However, very few researchers conducted observations on facility personnel’s field activities to acquire O&M related data and knowledge before they proposed their systems for O&M. As one of the few examples, Lee & Akin [55] collected 618 information instances by observing O&M fieldworkers maintenance activities and grouped them into 20 information types to develop an O&M information model. This model is utilized in the development of an Augmented Reality-based O&M fieldwork support application. Even though these studies proposed useful tools for O&M personnel, the effort of understanding the current practice by shadowing and observing facilities managers or technicians, as in Lee & Akin’s research [55], is seldom discussed in these BIM-for-maintenance articles.

3.1.2. Data exchange and system integration

Date exchange and the integration of separate systems are extensively discussed. To tackle the interoperability issue, some studies adopted Industry foundation classes (IFC) as the data exchange schema between BIM and CMMS [62,65], EIC [68], GIS [69], and BAS [71]. Others used commercial software applications to perform the data exchange, such as AutoCAD Civil 3D as a means of data exchange between BIM and GIS [56] and Revit DB Link to enable exchanging data between BIM and CMMS [72]. The concept of Central Facility Repository (CFR) proposed by the General Services Administration (GSA) describes the comprehensive information system built around a central facility database, which serves as the data foundation for FM-related software applications [76]. Although CFR is a promising development direction,



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Facility O&M in general	0	0	0	1	3	7	18	21	29	37	47	55
Energy management	0	0	0	0	4	5	7	15	21	27	35	37
Emergency management	0	2	2	2	3	5	11	15	21	24	27	31
Maintenance and repair	0	0	0	0	1	3	6	11	13	16	18	21
Security	0	0	0	0	0	0	1	2	2	3	3	3
Alternations/relocation/move management	0	0	0	0	0	0	1	2	2	3	3	3

Fig. 4. Cumulative number of reviewed BIM journal publications on each O&M activity per year.

Table 2
Summary of studies on BIM-enabled maintenance and repair.

Article	Research Goal	Functionality	Innovative algorithm/framework/system proposed	Experiment/Case study
Lin & Su [54]	Proposing a BIM-based FM system for maintenance staff	– Information accessibility	BIM-based facility maintenance management (BIMFMM) system	Case study of a commercial building project in Taiwan
Lee & Akin [55]	Proposing a system to improve efficiency in O&M fieldwork	– Information accessibility – Augmented visualization	Augmented Reality-based Operation and Maintenance Fieldwork Facilitator (AROMA-FF)	Experiments on an educational facility in a virtual reality environment
Liu & Issa [56]	Investigating how to use GIS and BIM to obtain facility O&M information	– Information accessibility	None	None
Shen et al. [57]	Providing a decision support tool for facility management and maintenance	– Information accessibility	– "BIM Octopus" – An agent-based web services that loosely integrates multiple systems	Case study conducted within a research facility. However, no specific data or experiment detail is presented in the article
Motawa & Almarshad [58]	Developing a decision support tool for preventive/corrective maintenance	– Information accessibility – Decision making support	A knowledge-based BIM system for building maintenance	None
Irizarry et al. [59]	Proposing a conceptual ambient intelligent environment for facility managers	– Information accessibility – Augmented visualization	A conceptual BIM-MAR (mobile augmented reality) system	None
Koch et al. [60]	Proposing a natural marker-based AR framework that can support FM operators	– Information accessibility – Augmented visualization	A natural marker (such as exit signs and position marks of fire extinguishers) based Augmented Reality framework	Case study of an educational building in Germany
Lin et al. [61]	Proposing a method that integrates 2D barcode and BIM for FM	– Information accessibility	A mobile automated BIM-based facility management (BIMFM) system	Case study of a commercial building project in Taiwan
Yang & Ergan [53]	Understanding the efficiency improvements provided by FM information visualization	– Information accessibility	A visualization platform to support troubleshooting of HVAC-related problems	User studies are conducted on HVAC mechanics
Motamedi et al. [62]	Providing a BIM-based framework for failure root cause detection	– Information accessibility – Failure root cause detection	An FM Visual Analytics System (FMVAS)	Case study conducted within a research facility in Canada
Yang & Ergan [63]	Providing an approach to increases the efficiency of HVAC-related troubleshooting process	– Information accessibility – Failure root cause detection	A system to identify applicable causes and retrieve information for HVAC-related problems	Experiments on an educational facility in the U.S.
Golabchi et al. [64]	Proposing an approach that uses BIM to develop algorithms for automating FM decision makings	– Information accessibility – Failure root cause detection	A BIM plug-in that uses a fault detection and diagnostics algorithm to automate the process of detecting malfunctioning HVAC equipment	Case study conducted within a university building in the U.S.
Shalabi & Turkan [65]	Improving the data quality for corrective maintenance by utilizing BIM	– Information accessibility	– A schema that integrates corrective maintenance data in BIM – A process that uses IFC-BIM to link alarm reports of equipment failures and the related maintenance information from Computerized Maintenance Management Information System (CMMS)	Experiments on an educational facility in the U.S.
Lee et al. [66]	Proposing a method that improves the effectiveness of pipeline maintenance	– Maintainability analysis	A method that evaluates pipeline maintenance accessibility with visualization and provides a suitable traffic flow for engineers	A usability test was conducted.

current BIM-O&M studies seldom show the effort of establishing the CFR. Rather than creating a comprehensive CFR, loosely coupled system integration solutions are more commonly used approaches [57,62,65,71]. Shen et al. [38] claimed that the most promising system integration approach for the construction industry is the "distributed loosely coupled integration solution using intelligent agents and Web services technologies" because using a single central repository to store all the information is not a viable option due to "the fragmented nature and adversarial behavior that characterizes the industry" [57,77]. Using this approach, Shen et al. [57] developed a system framework for providing decision support to facility management and maintenance. One advantage of this approach is that it has better generalizability than establishing a centralized comprehensive FM database. In this research, the proposed approach can theoretically integrate BIM with multiple building systems, such as HVAC control system, local weather station, building façade monitoring system, equipment and people tracking system, equipment condition monitoring system, fire response, and evacuation simulation system. However, the article did not show much evidence of the developed system prototype and the authors did not conduct experiments to validate its effectiveness. In another example, Motamedi et al. [62] integrated the data housed in CMMS, Condition Assessment System (CAS), Computer Aided Facilities Management (CAFM), and the data in Construction Operations Building Information Exchange (COBie) format. They linked these systems' databases by identifying a unique ID for each building element and using it in all related applications. This kind of loosely coupled integration lies the interoperability foundation for automated data transmission among the existing and proposed building systems. However, to fully realize the automation in data exchange still requires extensive work.

3.1.3. Data accessibility

Once the required information is ready-to-use, the next question is how to make the information available and accessible for facility managers when needed and how to present the information in an intuitional fashion such that maintenance personnel can easily comprehend it. To achieve these goals, researchers have adopted barcodes, RFID, and Augmented Reality (AR) together with BIM to facilitate maintenance and repair activities [55,59–61,78].

3.1.3.1. Barcodes and RFID. Barcodes and RFID tags serve as identifications of building items to access the relevant information which is linked with the corresponding objects in the database. By scanning the barcode or RFID tag of the item, the mobile device will present the corresponding 3D BIM component and its information, such as instruction manuals, photos, videos of operations, maintenance history, and manufacturer information, etc. [61,79]. The RFID has some advantages over the 2D barcode. RFID tags can be scanned from a distance and do not require line-of-sight or clean environments, which are necessary for 2D barcodes [79]. Additionally, each RFID tag has a chip that can store some modifiable data, which gives the RFID tag some flexibilities when used in an environment not connected to the remote information server (ibid.). The RFID also has some shortcomings, including the interference among each tagged component and the interference between the tagged component and some materials [79,80].

3.1.3.2. Augmented Reality (AR). By providing the superimposed geometric representation on the physical space along with the relevant BIM-based facility information in real-time, AR provides a suitable interface for O&M fieldwork support [55,59,60]. Similar to barcode and RFID-based systems, AR systems also require installing identification tags on facility items to identify them. As pointed out by Lee & Akin in [55], the computer vision-based AR technology can only recognize pre-defined physical markers to identify building components. Hence, the proposed AR-based BIM-maintenance system will not function properly if the markers cannot be seen clearly. Another challenge is that deploying physical markers to all the maintainable building components is neither economical nor realizable. These issues were partially addressed by a later study conducted by Koch et al. [60], who used natural markers (such as exit signs, position marks of fire extinguishers, and signs with textual information hints) as the defined visual markers that can be captured by the BIM-AR system. The relative position between the visual marker and the user, together with the camera's orientation, are used to locate the user's position; hence the maintenance related information can be accurately displayed on the screen, overlaying on top of the identified equipment. This system still has some limitations. It fails to locate the user's position and orientation when (1) no pre-defined natural marker is in the camera view, (2) the distance between two markers is larger than 10 m, and (3) the same marker appears at multiple locations (ibid.).

3.1.4. Fault detection and diagnosis

In addition to providing information, BIM-based O&M systems can also analyze maintenance and repair tasks such as equipment fault detection and diagnosis (FDD). Researchers have shown ways of improving maintenance and repair procedures by leveraging BIM's visualization and analysis capabilities to detect and locate system faults [64,81] and identify failure cause–effect patterns [62,73]. One major challenge of research in this area is to validate the proposed BIM-FDD system because a building typically does not have enough equipment failure work orders at a time. For example, Motamedi et al. proposed a system that provides visual analytics to support facility managers' cognitive and perceptual reasoning when making decisions and addressing issues [62]. Even though the prototype implementation and data transmission process were clearly demonstrated in a case study, the proposed system was only tested on one incident of equipment failure. Whether this system will work properly or not in a different situation remains to be tested. Yang & Ergan [63] conducted an extensive experiment on their BIM-enabled HVAC-troubleshooting system by using simulated test beds. They had to use synthetic work orders, which were created by recombining the characteristics of real work orders, to test the system because the existing FM work order databases did not contain enough information. The conclusion that the proposed system was effective assumes that the test beds can replicate real-world scenarios, which requires more discussions to justify.

3.2. Emergency management

Current research on BIM applications in emergency management focuses on emergency evacuation path planning/finding, indoor localization, fire emergency simulation and analysis, and facility safety management. The major research developments of BIM applications in facility emergency management are summarized in Table 3.

3.2.1. Pathfinding

Pathfinding is a fundamental issue in an emergency evacuation situation. It generally refers to "finding the shortest path connecting two points, while avoiding collision with obstacles" [82] but pathfinding in the context of emergency is much more demanding. During an emergency, the evacuees need to be directed to safe locations while avoiding potentially dangerous areas; the first responders need to find the trapped evacuees as soon as possible while ensuring their own safety. Moreover, the shortest path is not necessarily a safe path in many cases. Determining the optimal path and providing guidance to evacuees and first responders require not only comprehensive building information and real-time situation awareness, but also intelligent algorithms that can analyze the situation and support decision making. By providing both accurate 3D geometry and semantic information on a building, BIM can serve as the data source, the user interface, and the analysis platform for pathfinding and evacuation guidance during an emergency [82,86,87].

Table 3
Summary of studies on BIM-enabled facility emergency management.

Article	Research Goal	Method	Functionality	Experiment/Case study	Research Limitations
Lin et al. [82]	Proposing a path planning method for 3D indoor space using IFC.	– Traditional Fast Marching Method (FMM) and the revised FMM in the one-story case – In the multi-story case, the extended algorithm considers the stairs or elevators as the transit nodes of the path	Path planning	Case study of a library in China	The system prototype can only process a building with a single stair or elevator
Lee et al. [83]	Proposing a real-time emergency response approach	– The sensor information is integrated by the Ubiquitous Sensor Network (USN) Gateway developed by the authors – The facility information and sensor information are linked by Urban Object IDentification (UOID)	– Emergency monitoring – Unified facility management	Experiment in two scenarios – a burst of a water pipe and a physical impact on a road guardrail	The proposed system is only tested on two scenarios, which are not demonstrated in detail
Leite & Akinci [84]	Presenting an approach for vulnerability assessment in building emergencies	– Creating flexible search mechanisms by adopting a hybrid faceted-retrieval mechanism – Graph theory is used to address the issue regarding comprehensiveness versus information overload	Vulnerability assessment	User tests with ten subjects	This research assumes that the threat and its location are known. The approach only handles threats that are traceable by either the buffer or building system
Li et al. [85]	Introducing an indoor localization algorithm for building emergency response operations	The algorithm uses radio frequency (RF) signal data collected by sensing devices and incorporates building geometric information in BIMs. A maximum likelihood estimation method is used to estimate the locations of targets	Indoor localization	Experiment in two simulated building emergency scenarios	Various environmental factors that may affect the localization results are overlooked in simulations
Tashakkori et al. [86]	Proposing an IFC-based Indoor Emergency Spatial Model (IESM).	The IESM integrates 3D indoor information required by first responders with outdoor geographical information to improve situational awareness pertaining to both building interiors and their interactions with outdoor components.	– Pathfinding – Emergency information access	Experiment in three simulated campus emergency scenarios	The integration and interactions with the outdoor environment are not discussed in detail.
Chen & Chu [87]	Enabling automated in-building routing decisions by using a BIM-converted graph.	– Medial axis transform (MAT) is used to retrieve building geometry from a BIM to construct the graph, which is used to conduct the network analysis. – A time-dependent vehicle routing problem (TDVRP) model is adopted for rescue routes planning.	Pathfinding	Four test runs	The proposed approach's effectiveness has not been validated by simulation or comparison with other approachs. The analysis is limited to one building floor.
Bloch et al. [88]	Proposing an approach that provides building information for search and rescue teams.	– Identifying the collapse pattern by comparing the as-built BIM and the "as-damaged" BIM, which is derived from a laser scan after the earthquake. – The selection method uses the least sum of point distances and Modal Assurance Criteria algorithms.	– Emergency information access	Simulation with a two-story structural frame	The model used in the simulation includes only structural elements. The damage type considered is limited to the joints rotational failure.
Isikdag et al. [69]	Investigating whether BIM can benefit the processes of site selection and fire response management.	– A literature review and two group interviews – A set of software components that extract information from IFC are proposed and validated.	– Site selection – Fire response management	Two test cases	The proposed system is only evaluated based on interviewees' perceptions.
Rüppel & Schatz [89]	Understanding the decision process of an endangered person during an emergency.	Using BIM and engineering simulations to build serious game scenarios.	Human behavior simulation during fire	A validation experiment was planned but not conducted in this study	The integration of BIM and the game engine is not demonstrated in detail.
Abolghasemzadeh [90]	Proposing a method for BIM-enabled building fire egress analysis.	– An algorithm that integrates the BIM and fire simulations. – Additional factors are considered, such as the occupants' familiarity with the building.	Egress analysis	None	No experiment or case study is conducted to validate the proposed method.
Chen et al. [91]	Proposing a method that uses a micro-GIS to analyze 3D spatial data for fire-fighting simulations.	A 3D geometric network model (GNM)-based, BIM-supported framework is proposed for fire-fighting simulation.	Firefighting simulation	A fire-fighting drill	The data of building sensors and traffic sensors are not integrated into the proposed system.
Li et al. [92]	Introducing a BIM-centered beacon deployment algorithm for locating first	– The proposed algorithm uses the building geometric information in BIM to compute the space division.	– Indoor localization	Two building fire emergency scenarios were simulated	The computational efficiency is low in processing building geometries. The real-world

(*continued on next page*)

Table 3 (*continued*)

Article	Research Goal	Method	Functionality	Experiment/Case study	Research Limitations
	responders and trapped occupants during fire.	– Metaheuristics are used to find optimal sensor deployment that achieves a balance between the localization accuracy and on-scene deployment effort.	– Reducing the effort of deploying a sensor network		environmental factors that impact RF signal propagation are simplified.
Wang et al. [93]	Integrating BIM and virtual reality (VR) technologies to establish an adaptable immersive serious game environment for fire emergency simulation.	Information from BIM is imported into the video game engine Unity3D to create a VR environment.	– Real-time two-way information updating – Emergency awareness training	Experiments were conducted in a university building	The indoor localization function assumes people can use mobile devices to scan artificial markers during emergency.
Li et al. [94]	Presenting a comparative assessment of a radio frequency based indoor localization framework, which can provide first responders with timely access to accurate location information.	The authors assessed the proposed localization framework with two algorithms –EASBL (Environment-Aware radio frequency beacon deployment algorithm for Sequence Based Localization) and the IMLE (Iterative Maximum Likelihood Estimation) – under different situations and emergency scenarios, and between simulations and field tests.	– Indoor localization	Both simulations and field tests were conducted	The test bed and emergency scenarios have limited representativeness. Mobile nodes are required to collect radio frequency signal data and transfer the data to a remote server.
Wang et al. [95]	Presenting a BIM-based system that performs evacuation assessment, escape route planning, safety education, and equipment maintenance.	The evacuation assessment module integrates BIM with a Fire Dynamics Simulator to evaluate the ability to evacuate in case of fire. The escape route planning module utilizes BIM to determine whether the distance of an escape route is acceptable. The safety education module presents hazardous areas, videos of escape routes and directional maps to educate the occupants. The equipment maintenance module is implemented in a web-based prototype to support maintenance tasks.	– evacuation assessment – escape route planning – safety education – equipment maintenance	A case study was conducted in Taiwan	The system design was not demonstrated in detail, especially the escape route planning module. No path planning algorithm was given.
Wetzel & Thabet [96]	Presenting a BIM-based Safety for Facilities Management (SFFM) framework to categorize, consolidate, process, and present safety information to FM personnel.	The safety information for FM staff is identified, organized, and categorized, which is executed through research methods structured within the framework of Six Sigma's Define-Measure-Analyze-Design-Verify (DMADV).	Providing safety information for FM personnel	None	The system's functionality and usefulness should be tested by a pilot study.
Cheng et al. [97]	Presenting a system that integrates BIM and wireless sensor networks for building disaster-prevention management.	BIM is used to construct a Fire Prevention and Disaster Relief System, which integrates people location information, evacuation/rescue route, and mobile guidance device to display the real-time fire information in three dimensions.	– Pathfinding – Evacuation guidance – Monitor disaster areas	A case study was conducted in Taiwan	The localization mechanism does not consider Bluetooth sensors being destroyed in the fire.
Shiau et al. [98]	Presenting a fire-control surveillance and management system	The system is developed based on the BIM model, an SQL server, and a Windows environment. BIM is integrated with fire control equipment.	– Fire control surveillance – Equipment data inquiry – Spatial usage data inquiry	A case study was conducted in a university in Taiwan	No system test or validation was conducted.

Graph Theory, a well-studied area in Computer Science, is widely used to explore spatial navigation and pathfinding problems [84,87,99]. A graph in this context is made up of nodes which are connected by edges. BIM can be used as the data input to construct a graph, in which nodes are representing building spaces and edges are representing the connections among them. For instance, Chen & Chu [87] used an approximated medial axis transform (MAT) algorithm to construct a graph from the BIM. Comparing to other approaches such as the Visibility Graph [100], the graph generated by MAT contains fewer nodes, which means lower computational resource demand [87]. Even though this research extensively discussed the method of graph construction from BIM and the improved algorithm for emergency rescue rout calculation, the BIM is only used to generate a two-dimensional (2D) floor map and the constructed graph can only represent one story of the building. The semantic information in BIM is not utilized either. Using IFC, Lin et al. [82] proposed an approach that can extract both geometric and semantic information of building components from BIM, including walls, doors, columns, furnishing elements, distribution elements, and spaces. Moreover, by considering the stairs and elevators as the transit nodes of the path, their algorithm is applicable to convert multiple building stories into a single graph. However, the system prototype they developed in the case study can only process a building with a single stair or elevator. The challenges of analyzing the graph generated from BIM with multiple stairs and elevators, and how to resolve them remain to be studied.

3.2.2. Indoor localization

During an emergency, the real-time locations of first responders and occupants are critical for improving the rescue efficiency and reducing fatalities and injuries [85]. Although indoor localization is a fundamental module for many emergency evacuation and rescue system, BIM applications research in this area is scarce. The BIM-based emergency evacuation system proposed by Wang et al. [93] requires users to scan the artificial markers distributed in the building with mobile devices to locate their positions. This assumes that the evacuees can find the markers and have the equipment to scan them during a fire emergency. Cheng et al.'s system uses the Bluetooth sensors distributed in the building to detect fire and to locate the occupants through the mobile app they developed [97]. When the Bluetooth sensors detect sufficiently high temperature or smoke levels, the system will sound the alarm and calculate the fire-outbreak locations and the evacuation/rescue routes in the BIM. The evacuee and the first responder must use the mobile app for navigation. The app can execute in the background hence the evacuees do not need to operate any devices proactively. Neither [93] nor [97] have tested the robustness of the systems under the situation that the markers or sensors being damaged in the fire emergency. To address this issue, Li et al. [92] proposed a BIM-centered radio frequency (RF) beacon deployment algorithm that provides an optimized beacon deployment plan to locate first responders and trapped occupants during a fire. The system they proposed can locate the users who carry smartphones or any other RF-based devices that can communicate with the beacons deployed according to the plan generated by the algorithm. This algorithm showed high robustness against loss of beacons – the accuracy of determining whether there are people in a certain room or not could remain "above 80% when up to 54% of the deployed beacons were damaged". One drawback of this approach is the necessity to deploy an ad hoc sensor network, which does not utilize any existing sensors in the building, from scratch. A later study conducted by Li et al. [85] presented an indoor localization algorithm that uses RF signal data collected by existing sensors in a building. This algorithm also showed high robustness against loss of sensors.

3.2.3. Fire and life safety

The most common emergency for buildings is fire. Basically, all the BIM-based emergency management systems are applicable to the fire emergency. BIM applications in fire simulation is a compelling research area because the occupants' behavior during a fire cannot really be investigated by real-world experimentation [89]. BIM offers a comprehensive digital environment in which all building safety-related information is available for simulations, e.g. the fire egress simulation [90]. BIM-based serious games with Virtual Environment (VE) have been created for evacuation training [93] and exploring the effect of building condition on human behavior during a fire [89,101]. BIM is integrated within the game and hence the game designers are released from the time-consuming modeling work when creating the 3D game environment [89,93,101].

Comprehensive fire safety management systems can be built based on the pathfinding and indoor localization. For example, Wang et al. [95] developed a BIM-based comprehensive fire safety management system which has pre-emergency functions include evacuation assessment, escape route planning, safety education, and fire safety equipment maintenance. Most of the proposed systems' effectiveness has been validated through simulations or drills, such as in [69,91,93,95,97]. However, the more comprehensive these systems are, the more work would be required to deploy them. Extracting useful information – such as the locations of fire extinguishers, the access control information, etc. – from building systems (BAS, CMMS, etc.) or utilizing data generated by existing sensors could partly reduce the efforts of deploying these fire safety management systems. However, it is rarely discussed in the reviewed studies.

3.3. Energy management

Buildings are not operated energy-efficiently [102] and consume 30–40% of global energy annually [103]. Energy management is challenging by nature because optimizing energy consumption requires understanding the real energy needs and adjusting operation activities accordingly. To tackle this issue, BIM is leveraged in providing the building geometry and material information [70,104–111], integrating and visualizing the energy-related information [112–116], assessing energy performance and simulation [117–120], and energy optimization [70,71,113,121–124]. The major research developments of BIM applications in energy management are summarized in Table 4.

3.3.1. BIM as a data source for energy analysis

Among the many publications on building energy simulation and management in the past decade, the ones that have discussed BIM applications only account for a little proportion. This is probably because regardless of the detail level of a BIM developed during design and construction, it does not usually contain the data required by energy simulation [105]. Thus, populating energy simulation related information into existing BIMs developed by others is a redundant work for researchers who are already skilled with prevailing energy simulation and analysis software programs (such as EnergyPlus and IES-VE), most of which support 3D models. However, models created in these programs are not commonly considered as BIMs since they usually contain only 3D geometry and energy-related information.

The early stage of BIM application in energy management is using BIM to provide the basic building information for energy analysis. By importing the building geometry and/or components' physical characteristics information from BIM into energy analysis tools, researchers can avoid a part of the work required to recreate the building model in those tools [70,104–111]. The level of interoperability between the BIM authoring tool and the energy analysis tool determines the efforts required to make the data transfer. For instance, Crosbie et al. [105] could import the BIM developed in Revit directly into IES-VE because Revit has an IES-VE add-on that enables the direct linkage. Raftery et al. [106] had to use a tool named GST/IDF Generator to convert the IFC file into the EnergyPlus input data file IDF. The research studies that simply use BIM as a basic building information data source typically focus their discussions on the specific energy analysis methods rather than examining how BIM can improve the analysis process or provide

Table 4
Summary of studies on BIM-enabled energy management.

Article	Research Goal	How BIM is utilized
Ahmed et al. [104]	To connect the building design with the building performance by data mining techniques, hence to investigate how to improve energy efficiency	A web-based Energy Building Information Model (eBIM) is adopted to obtain building components' physical characteristics
Crosbie et al. [105]	To develop virtual collaborative 'life cycle' building tools to support energy efficient building design, operation and retrofit	The BIM developed in Revit Architecture is used to avoid recreate geometry in IES-VE
Raftery et al. [106]	To demonstrate a systematic, evidence-based methodology for calibrating building energy models	An IFC model was created to provide the building geometry for the EnergyPlus input data file (IDF) through GST/IDF Generator
Costa et al. [125]	To propose an integrated toolkit designed to assist energy managers in systematic building energy management	The BIM is used for structured building performance definition. The Performance Framework Tool takes an IFC file as its input, defines and appends scenario definitions, and exports the file in IFC format again
Gokce & Gokce [107]	To propose the Holistic Multi-Dimensional Information Management System that can store, integrate, analyze data sets from multiple sources such as sensing devices and BIM	The IFC model is used as a data source for the proposed system
Ahn et al. [108]	To demonstrate two approaches – full automated interface and semiautomated interface – that enables information transition from IFC to EnergyPlus input file, IDF	The geometric information in IFC is converted to IDF (an input file for EnergyPlus)
Dong et al. [114]	To propose a BIM-enabled information infrastructure for Fault Detection and Diagnostics (FDD)	The BIM is used to integrate the relational database and real-time data from BEMS for energy simulation and FDD
Gokce & Gokce [126]	To propose and validate the Multi-Dimensional Monitoring, Analysis and Optimization System that can store, integrate, analyze complex data sets from multiple sources such as sensing devices and BIM	The IFC model is used as a data source for the proposed system
Lawrence et al. [70]	To propose a paradigm for designing and operating buildings and their systems by leveraging Energy Informatics and cross-reality technologies	The BIM is the component in the proposed paradigm that provides basic building geometry and component information
Dobbs & Hencey [127]	To present an occupancy-predicting control algorithm for building HVAC systems	The BIM is translated automatically into a linear, time-invariant network that encompasses the dominant thermal processes
Gokce & Gokce [128]	To propose a model-driven holistic system architecture integrating monitoring and control systems of design, construction, and operation stages to provide optimized building operations	The IFC model is used as a data source for the proposed system
Marzouk & Abdelaty [115]	To present an approach that uses a wireless sensor network (WSN) and BIM to monitor thermal conditions in a subway	The BIM is used to visualize the readings of air temperature and humidity levels in the subway spaces
Alwan & Gledson [129]	To propose a conceptual framework for BIM-enabled integrated asset management strategy	The as-built BIM is a basic component of the proposed Asset Information Model
Corry et al. [121]	To propose a semantic web-based approach that assesses the performance gap between design intent and the real-time environmental and energy performance	An IFC model is created and each of its entity is mapped to an element in the OWL (Web Ontology Language) ontology by the IFCtoRDF (IFC to Resource Description Framework) conversion service
Gourlis & Kovacic [117]	To investigate the potential energy savings of existing industrial facilities through a case study on the thermal refurbishment of a historical production hall	A BIM is created to provide material type and quantity information
Hamza-Lup & Maghiar [109]	To propose a system that can provide web-based, real-time visualization and offline simulation of 3D thermal maps for residential and commercial buildings	The BIM is used to generate the X3D (an open standard for 3D computer graphics) thermal map of the building
Lee et al. [116]	To develop a BIM-enabled energy management platform that can monitor building energy consumption and support the facility manager to control the building equipment	The BIM is used to visualize the environmental and energy consumption data
Oti et al. [112]	To propose a framework for utilizing feedback loops from building energy consumption to improve design and facility management in a BIM environment	The BIM is used as the information platform to integrate the designed and actual energy consumption data
Yang et al. [130]	To introduce a framework for evaluating the energy implications of occupancy diversity (when and how occupants occupy a building)	The BIM is integrated to provide building geometries and HVAC system layouts as inputs for computing potential energy implications
Chou et al. [131]	To propose a system that can visualize the energy analysis results, provide residents energy saving tips, and identify the appliances that can be used jointly to consume all the solar PV-generated electricity	The BIM is used to provide the building geometry and material information to the Unity environment. The data in BIM is also integrated into the power consumption data sets by filling in each power socket's location and room information
Gerrish et al. [132]	To identify the barriers to implementing BIM for building designers and operators to visualize and manage a building's performance	The basic building geometry and performance related information in BIM is extracted by Dynamo and translated into JSON, a lightweight data-interchange format
McGlinn et al. [133]	To evaluate the usability level of a monitoring and control interface for energy efficient management of public buildings	The system is based on IFC that consists of two rule models to control and manage buildings adaptively
Natephra et al. [134]	To present a method to collect environmental and thermal data, and to integrate them with the BIM to be used for various applications during a building's O&M phase	The IFC model is imported into Rhinoceros with Grasshopper scripting to provide building component information

new methods for energy management.

3.3.2. *Energy consumption data integration and visualization*

Energy efficiency becomes an important consideration as early as the schematic design phase of a project, but the real energy consumption data is not available until the operation phase starts. Even though many software applications can perform energy simulation and analysis, there is always a deficit between design intent and real energy performance [121,135,136]. Collecting the real energy consumption data is critical to provide feedback for future design and simulation [135,136]. In the context of energy management, BIM with energy-related information is also referred as Building Energy Information Modeling (BEIM) [113]. Researchers have developed frameworks and/or systems to integrate BIM with the energy data extracted from multiple building systems, such as Building Management System (BMS) [112] and Building Energy Management System (BEMS) [113,114,116]. This requires a deeper level of integration than just using BIM as a data source. For example, Dong et al. [114] developed a data schema for a BIM-enabled real-time building energy Fault Detection and Diagnostics (FDD). This schema incorporates the FDD-related building information extracted from the BIM with the real-time data generated by sensors installed in buildings. FDD can be implemented by comparing the simulated baseline energy performance model and the real energy consumption. However, this research does not realize the seamless data acquisition and the FDD results are not visualized in the 3D model.

Many energy management studies have leveraged BIM's 3D visualization capability but only a few provided color-schemed visualizations reflecting the time-dependent energy consumption information. Natephra et al. [134] imported the BIM from Revit into Rhinoceros and incorporated it with time-coded thermographic images, which can visualize the changes of thermal information over time, by the Grasshopper plug-in. Thermal values were extracted from the thermographic images by the visual scripting of Grasshopper and presented on the BIM. Because those images were generated through infrared thermographic survey and indoor/outdoor dry-bulb temperature collected by sensors, the thermal information visualized in the BIM is the historical record rather than in real time. In the research conducted by Chou et al. [131], the data generated by building sensors is collected by a central database and integrated within the BIM housed in Unity (a visualization engine for video games) to visualize the spatiotemporal analysis results, which are generated by the temporal and spatial data analysis system they proposed. The authors developed a program to synchronize all communication between Unity and the database, hence a user can see the real-time energy consumption information and the analysis results in the virtual building. Lee et al. [116] used a Revit add-on named "web published model" to convert the BIM into a wpm file that can be published on the web. The web-based system they proposed uses predefined viewpoints to present the energy consumption information and analysis results on BIM, which means the 3D model in the system cannot be rotated, but only uses several predefined angles to represent the information of the user's interests. Another web-based system proposed by Hamza-Lup & Maghiar [109] can achieve 3D browsing by converting the BIM to X3D files and then publishing on the system. Because the X3D is an open modeling representation standard, this system is independent of proprietary software packages and their integration solutions.

3.3.3. BIM-based energy management systems

Researchers have proposed comprehensive systems that improve energy management by leveraging the BIM-enabled platforms that facilitates acquiring, storing, and processing energy-related information, thereby provide facility managers the capability (1) to monitor the energy consumption and to analyze the performance [70,104–109,112–116,121,123,125,126,128,131,133,137–141], (2) to perform energy simulation and forecast [105,109,117–119], (3) to visualize energy information through 3D model [112–116,140], (4) to acquire building control suggestions for energy conservation [105,131,133,142], (5) to monitor thermal condition [115,134,143], (6) to conduct fault detection and diagnosis [62,64,73,81,114,125], and (7) to assess the sustainability [144,145]. The roles of BIM in these systems are summarized in Table 5. Most of the reviewed research studies use BIM as the data source to provide building information (geometries, components' characteristics, etc.) to perform specialized energy simulation and analysis software applications, such as IES-VE and EnergyPlus [105,106,108]. BIM also serves as the platform to integrate energy consumption data [112–116,125,138,146], thermal sensor data [115,134], and enables information exchange among separated building systems [62,64,73,81,114,125]. Some studies make the BIM database as the information infrastructure of an expert system, which compares the actual energy consumption with designed benchmarks or the prediction model to identify discrepancies [112,114,121,127–129,133]. Knowledge of energy-related issues is captured to support facility managers in the decision-making on current problems, and to provide information for future building design and management.

3.4. Change/relocation management

Change Management (CM) in the Architecture, Engineering, Construction, Owner, and Operator (AECOO) context refers to an integral process related to all project internal and external factors that influence project changes; this process involves forecasting possible changes, identifying already occurred changes, planning preventive impacts, and coordinating changes across the entire project [147]. Research on integrating CM with BIM is scarce, especially in an O&M context. Pittet et al. [148] introduce a BIM-based ontology CM approach, named OntoVersionGraph, applied in O&M domain to manage change impacts, maintain consistency of knowledge, and provide the information required by each participant. "Ontology" in this context means heterogeneous information processable by machine and understandable by humans. The authors theoretically discussed the mechanism of OntoVersionGraph for multi-context and user-centered systems of CM in O&M. An example of making a hole in an existing wall to set a doorway was used to demonstrate how the proposed approach can be applied to a problem involving different actors with different views on an ontology. In the example, the change management processes from the architect's perspective, the electrician's perspective, and the BIM ontology perspective are described, respectively; the basic steps of each process involve change detection, change modeling, change semantics, change implementation, change propagation, and change validation. Even though the proposed approach appears to be applicable to all changes in a facility (e.g. replacement of building equipment, refurbishing the interior finishes, etc.), the authors did not present a more complicated example that involves multiple change tasks, which could be a better demonstration for the proposed approach's applicability for comprehensive changes. This approach has been applied to a commercial software application called Active3D (www.active3d.soprasteria.com). Empirical studies (e.g. case studies) using such BIM-based software tools for CM are still lacking and would be significantly beneficial to this research field.

The only journal paper involving the BIM application in relocation management we identified is a case study, in which a serious game is created to support healthcare personnel to learn their new facility [149]. Relocation for healthcare facilities is challenging because the personnel need to be well trained before relocating, otherwise it may endanger the health of patients. In this case study, BIM is used to provide data for the game scenarios and it shows a promising research prospect in gaming-based process simulation informed by BIM. However, the authors found that the data exchange between the BIM and the game engine Unity – even just importing and exporting geometry – is challenging due to the lack of interoperability between Unity and the BIM authoring tool Revit. This research was conducted from 2013 to 2014 and some research studies after this have addressed this interoperability issue, such as studies by [93,131]. Merschbrock et al. [149] highlighted the implementation process of the game but did not discuss the game development in detail, especially not the data exchange process between the BIM and the game engine. A framework for integrating BIM and the video game engine to support relocation management is yet to be studied.

3.5. Security

A facility's physical security goals involve controlling access, reducing theft, and preventing the interruption of the organization's mission [18]. Achieving these goals requires security experts' knowledge and experience of facility physical security assessment – the process of examining a facility and estimating the risk of it being penetrated without detection or appropriate response [150]. To reduce dependency on experts, computer simulation and expert systems are developed to assist security personnel. Researchers have been looking at using BIM for facility physical security assessment [150] and enhancing the access administration system [99,151].

Table 5
Energy management systems that involve BIM.

System function (s)	Role of BIM	Reference
Energy consumption monitoring and analysis	The building data source	[70,104–113,121,123,125,126,128,131,133,137–141,146]
	The platform to integrate data from BMS	[112–116,125,138]
Energy simulation and forecast	The building data source	[105,109,117–119]
Energy 3D visualization	The visualization platform	[110,112–116,140]
Informing building control	The building data source	[105,131,133]
Thermal condition monitoring	The spatial data platform to integrate sensor data	[115,134,143]
	The visualization platform	[134]
Fault detection and diagnosis (FDD)	The analysis platform for FDD	[62–64,73,81]
	The data infrastructure to enable information exchange	[62,64,73,81,114,125]
	The energy performance data storage	[125]
Sustainability assessment	The building data source	[144,145]

Graph Theory is adopted in the BIM-enabled security assessment domain, physical entities in BIM are converted to nodes and the connection relationships among them are converted to edges [99,150]. The nodes represent areas or zones, such as rooms, while the edges represent the possible paths, such as through doors and windows. Each edge has a weight or cost, typically indicating the difficulty level or delay associated with the path. For example, two rooms (nodes) have three paths (edges) that connect them, which are a door without a lock, a window, and a fixed interior partition. The weight/cost of these paths can be quantified as 1.0 for the door, 4.0 for the window, and 10.0 for the partition, representing the difficulty level or delay of going/penetrating through the path. After the BIM is converted to a graph, graph theory algorithms, such as Dijkstra's shortest path algorithm [152], can be used to analyze the security condition of each zone. To prove the concept, Porter et al. [150] tested their BIM-graph approach using a simple BIM involving two levels of symmetrical rooms. They performed a greedy search on the graph and identified the areas of weakness, hence to enable a designer to easily examine the rooms that tend to be intruded and improve them, thus improving the overall security of the facility. This study can be further improved in two aspects. The security assessment results generated by the proposed system can be further justified by comparing the results with the security experts' assessments. Moreover, experiments on larger buildings are still to be conducted to test this approach's applicability and identify challenges.

The physical access control in large-scale facilities is a difficult task because it requires efficiently comprehending complex environments to make informed access control decisions [151]. Skandhakumar et al. [151] proposed a BIM-enabled approach that supports access control management by "intuitively creating physical access control policies, conveniently managing physical access control systems, and effectively auditing physical access control logs". In this article, the authors only briefly discussed how this approach can support access control assessment by providing 3D visualizations, pathfinding functionality, and identification of potential inconsistencies within a policy rule set. The proposed approach framework and technical methods were not discussed in detail. In another study [99], Skandhakumar et al. proposed a graph theoretic representation of BIM, named "BIM graph", and demonstrated how it can be used in real-life access control application scenarios. The idea of BIM graph is similar to that of converting the BIM into a graph used for security assessment [150], which is discussed in the last paragraph. The difference is the BIM graph is a hierarchical graph in which all the nodes (representing spaces) and edges (representing portals) belonging to a certain story of the building are under the corresponding subgraph, which represents the story; while the BIM in [150] is converted to one single graph without any hierarchy. The authors [99] developed three BIM graph based algorithms – the pathfinding algorithm, the minimum security path algorithm, and the accessibility analyze algorithm – to automate typical access control functions such as pathfinding, consistency detection, and accessibility verification. The proposed BIM graph approach and its algorithms have not been tested by any experiment nor simulation. Case studies using the BIM graph approach for physical access control management would be beneficial to this research field.

4. Research gaps and recommendations for future research

The study of BIM-O&M has shown a rapid development momentum in the past decade. BIM has the potential to provide facility managers with a powerful platform to store, obtain, and process facilities' information. Table 6 summarizes the role of BIM in supporting each O&M activity and the interactions with related building systems. In the BIM-enabled O&M field, many important questions have not been answered and more advanced practical systems are yet to be invented. This section discusses the identified four research gaps of existing BIM-O&M studies – interoperability in the O&M context, understanding the underlying O&M principles for BIM implementation, and return on investment – and provides recommendations to address these issues. This section also presents three additional recommendations for future research, which are the potential BIM applications in hazardous waste management, ICT asset management, and user-centered O&M systems.

4.1. Interoperability in the O&M context

The challenges caused by inadequate interoperability is extensively discussed by different studies [4,17,154–156]. Realizing BIM's capabilities to support facility O&M tasks requires extensive software development work. Exchange data between emerging BIM-enabled systems and existing building systems, such as CMMS and BAS, remains a challenge. Studies that investigate interoperability solutions after the establishment of the BIM-centered database in the context of facility O&M are scarce.

The Cyber-Physical System Framework most recently developed by the National Institute of Standards and Technology (NIST) [157] provides a common language for describing interoperable CPS architectures in various domains so that these CPS can interoperate within and across domains and form systems of systems" (SoS) [158]. "Cyber-physical Systems" (CPS) are highly interconnected and integrated smart systems that include engineered interacting networks of physical and computational components [158]. CPS is an umbrella term and concept that represents multiple novel concepts with various potential applications – Internet of Things (IoT) [159], machine-to-machine (M2M) [160], industrial internet [161], smart city [162], digital city [163], etc. Typically, a CPS consists of the physical part – a device, a machine, or a building – and the digital or cyber part – the software system, communication network, and the data. The cyber part of CPS represents digitally the state of the physical part and impacts it by automated control or informing people of control actions.

The NIST CPS Framework can be used to analyze a CPS by breaking down the complex system into standardized components – Domains, Aspects, and Facets – that form a manageable and understandable summary (as Fig. 5 shows). The Domains are the industries that the CPS can be specialized and applied to, such as construction, manufacturing,

Table 6
The role of BIM in supporting each O&M activity and its interactions with related building systems.

The Role of BIM	The Interactions between BIM and Related Building Systems	O&M Activities and Reference
The building data source	• BIM provides the basic building information (3D geometry and semantic data) for the proposed systems. • Elements in BIM are linked with Barcodes, RFID tags, and AR systems to enable timely data access.	Maintenance and repair [53,55–58,60–65,68–75,79,153] Emergency management [69,82,83,85–97] Energy management [70,104–113,117–119,121,123,125,126,128,131,133,137–141,144–146] Change/relocation management [148,149] Security [99,150,151]
The data infrastructure to enable information exchange	• IFC is used as the data exchange schema between BIM and CMMS, EIC, GIS, and BAS. • Commercial software applications, such as AutoCAD Civil 3D and Revit DB Link, are used to exchange data between BIM and building systems.	Maintenance and repair [38,56,57,62,65,68,69,71,72,77] Energy management [62,64,73,81,114,125] Change/relocation management [148]
The platform to integrate data from sensors and building systems	• Related data are extracted from building systems such as BAS, CMMS, BEMS, EIC, and incorporated in BIM. • BIM provides a semantic layer for accessing the sensor data linked. • BIM serves as the "hub" for the proposed loosely coupled systems that connect multiple building systems	Maintenance and repair [56,57,62,65,68–75] Emergency management [83,84,97] Energy management [112–116,125,134,138,143]
The analysis platform	Applications are developed on the BIM-based platforms to perform: • maintainability analysis, • emergency evacuation path planning/ finding, • indoor localization, • fire emergency simulation and analysis, • fault detection and diagnosis, • sustainability assessment, • energy simulation and forecast.	Maintenance and repair [58,59,62–64,66] Emergency management [69,82,86,88,90,91,93] Energy management [62–64,73,81]
The visualization platform	• BIM provides intuitive 3D visualizations to locate building components and to support troubleshooting in proposed maintenance systems. • BIM-based 3D indoor navigation functions are incorporated in the proposed emergency management systems. • Energy management systems use color-schemed visualizations in BIM to reflect the time-dependent energy consumption information. • The 3D user interface of proposed systems is based on BIM.	Maintenance and repair [59,60,153] Emergency management [69,82–84,86,87,90,91,93 95,97] Energy management [110,112–116,134,140] Change/relocation management [148] Security [151]

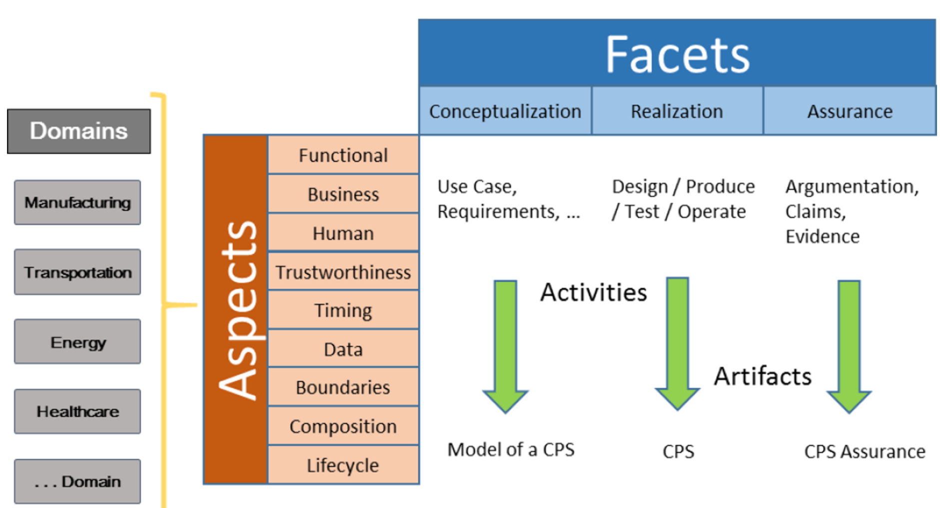


Fig. 5. CPS Framework – Domains, Facets, Aspects [158].

transportation, and energy. The Aspects are high-level groupings of cross-cutting Concerns of CPS – interests in a system relevant to one or more stakeholders – involving functional, business, human, data, etc. [164]. The three Facets, namely conceptualization, realization, and assurance, deal with three major questions, respectively, which are: (1) what things should be and what things are supposed to do, (2) how things should be made and operate, and (3) how to prove things work the way they should [164].

BIM has the potential to serve as the "cyber" part of the building. If we consider the existing and hypothetical BIM-O&M systems as CPS, the NIST CPS Framework can aid researchers and practitioners in determining these systems' properties, and provide guidance such that two BIM-O&M systems' architectures, independently derived from or tailored to this Framework, are in substantial alignment [158]. This alignment can be achieved by identifying the "Pivotal Points of Interoperability" (PPI), which are the overlapped concepts, standards, protocols, and data interfaces among multiple CPS [165]. One of the reasons for the interoperability challenge in BIM-O&M is the abundance of standards and technologies available to use. For example, there are various building automation protocols, such as BACnet, Modbus, ZigBee, C-Bus, etc. Normally, researchers and technology providers work on the specific interoperability issue between two systems, standards, or protocols, such as extracting information from the IFC model and importing into the CityGML model [166–168], or utilizing information housed in BIM to fill in data fields in CMMS [169]. These efforts are valuable, but the scattered demands of interoperability are innumerable because the increasing number of systems and tools designed for certain O&M tasks are emerging. To understand these systems' mechanisms and make multiple of them interoperable become exceedingly difficult. Using the NIST CPS Framework to discover the PPI through analysis of prominent technologies in BIM-O&M applications, promises to reveal common choices – concepts, standards, protocols, and data interfaces – by researchers and developers, and thus will produce an overall picture that shows the critical work needs to be done to achieve interoperability in the BIM-O&M context. After the PPI for BIM-O&M identified, researchers and developers can be more focused on these critical interoperability issues and develop more specified methods and techniques to address them.

4.2. Understanding the underlying O&M principles for BIM implementation

The most commonly used research method in the BIM-O&M area involves proposing an approach/framework/system, developing a prototype, and testing it with case studies or simulation (Fig. 3). However, we believe that currently there still exists a gap in understanding of the underlying FM principles that can be generalized. Although the O&M workflow and procedures followed by different organizations can be diverse and there is no one-size-fits-all approach to BIM adoption [170], knowledge such as the common BIM data requirements for O&M, current BIM data delivery and presentation methods, expectations of new technology, and hypothetical BIM-O&M use cases, will serve as the foundation for developing more powerful and generally applicable BIM-based systems and solutions for facility O&M. To identify, summarize, and, if possible, standardize these principles requires extensive work. Currently, the surveys aiming to develop this kind of knowledge are limited [13,169,171–179] and more studies are still in demand. For example, in 2012, Becerik-Gerber et al. [171] conducted a comprehensive survey to identify the application areas and data requirements for BIM applications in the FM field. This research discussed the general FM data requirements for all types of facilities. However, the BIM data requirements can be varied for different O&M practitioners working on different types of facilities. More focused surveys on common BIM data requirements for specific building types – hospitals, residential buildings, commercial complexes, etc. – and for specific O&M tasks have yet to be conducted. The BIM-O&M field would benefit immensely from surveys that target this gap. In addition, one of the major goals of the emerging BIM-O&M systems is to reduce dependency on experts. This requires acquiring experts' knowledge and incorporating it into the systems. Obtaining the knowledge also requires extensive surveys.

Understanding the underlying O&M principles for BIM implementation is the first step for BIM-O&M standardization, which is highly in demand in the BIM for FM domain. As pointed out by Pishdad-Bozorgi et al. [169], standardization – such as consistent naming conventions and specified data requirements – is vital for project level interoperability when developing BIM for FM. Industrial standards such as ISO [180] will reduce the need for customization in each project and enable streamlined data exchange between BIM tools and facility management systems. By creating consistency and eliminating redundancies and so many resources can be saved. Industrial standards can facilitate BIM's applications in the FM domain, especially when BIM's economic benefits are realized in more efficiently implementing various FM activities. Currently, new ISO standards are developed to facilitate FM by providing a common language and defining standardized requirements [54] but well-established BIM-FM standards are yet to be developed.

To further explore the underlying O&M principles that can facilitate BIM implementation, the following topics are recommended for future research:

(1) *Defining the general data requirements specifically for each O&M task, facility types, and identifying the stakeholders who should provide the data at a certain point throughout the facility life cycle*. Relevant research studies involve [171,173,176,178] but all of them discuss the general FM data requirements without identifying and discussing the specified requirements for each facility type or for each O&M activity. A Model View Definition (MVD) defines a subset of the IFC schema that is needed to satisfy one or many data exchange requirements [181]. By using Information Delivery Manual (IDM) method [182] to capture and specify processes and information flow, researchers can create MVDs that specify what should be expected from IFC models for each O&M task, and thus streamline the data exchange between BIM and relevant facility management systems.
(2) *Identifying the areas of inefficiencies that can be facilitated by BIM in current O&M practice, such as the work done in* [13,175], *and challenges encountered in the BIM implementation process, such as the discussions in* [169]. This type of research is typically conducted through empirical methods such as questionnaire surveys, interviews, and case studies. The research findings may not be generalizable to all circumstances, even though the research is rigorously conducted, because of the various facility O&M profiles of different organizations. Therefore, more empirical studies are still in demand to provide researchers a clear picture of the current status – what are the areas of inefficiencies that can be improved by BIM, what are the expectations of BIM-O&M applications, what are the challenges have been encountered, and what challenges can be expected – and to provide a comprehensive map that shows the directions for future BIM-O&M developments.
(3) *Identifying and discussing the process changes brought by BIM. BIM is a disruptive technology that already changed the design and construction industry*. Facility O&M, however, has not fully embraced the benefits of BIM yet. Soon, the process change brought by the technology innovation will be a pressing issue. BIM has enabled integrated design and construction and has provided the technology foundation for Integrated Project Delivery (IPD). As the BIM-O&M applications continue developing, we can expect more discussions on the process changes in this area.

4.3. Return on investment (ROI)

Multiple studies propose systems that would inform and support decisions made by facility managers when performing facility O&M tasks. These systems integrate building information models, perform comprehensive analysis, provide intuitional 3D visualization, and offer real-time access to relevant information for users, examples can be found in [54,55,59,62,83,86,93,109,133,134]. However, even though the benefits of these systems are understood and accepted, only a few studies have examined the quantified efficiency improvements brought by their proposed systems [53,55,61].

More research is needed to investigate the BIM-O&M systems that achieve a reasonable ROI. For example, the prototype of visualization platform for HVAC corrective maintenance proposed by Yang & Ergan is able to achieve a reduction in task completion time by 58%, as compared to current practice, which is attributed to searching for information from documents [53]. The median of time used for the task is decreased from 12 min and 32 s to 5 min and 12 s. In another study, the proposed approach of using mobile BIM/2D barcode-based system when performing maintenance work can save the user approximately 6–40 s per task; while in the current paper-based approach each task takes 12–90 s to complete [61]. These two systems have shortened the completion time for each task. However, when considering the extensive efforts need to be made to create and maintain the comprehensive BIM, develop and configure the system, place the barcode, etc., one may question if the ROI is justified. The practical value of these systems may be realized when many maintenance tasks need to be executed in large and complex campus facilities.

One challenge of conducting research on ROI of BIM applications in O&M is the lack of means to quantify the influences brought by BIM. A clear understanding of the cost savings associated with implementing BIM-related technologies in facility O&M is essential for the justification of ROI. However, unlike the benefits of BIM applications in design and construction – shorter design iteration cycles, time and money saved through reducing clashes, etc. – that can be perceived and quantified relatively easily, the benefits of BIM-O&M tend to require a longer time span to balance out the costs. Therefore, to assess a BIM-O&M application's ROI requires a better understanding of its influences on the life-cycle costs (LCCs) of the facility and its components.

A historical data-based Life Cycle Cost Analysis (LCCA) framework is a solution for the issue of ROI justification of BIM-O&M applications. LCCA is a method for assessing the total cost of the facility ownership, involving all costs of acquiring, owning, and disposing of a building or building system [183]. Currently, the LCCA method is mainly used to compare different alternatives in the design stage [184], but understanding the LCCs is also important for decision makings during the operation phase, such as retrofitting, refurbishment, renovation, and incorporating a new O&M tool or system. However, despite its importance, LCCA has found limited application in the AECOO industry so far. Two of the main barriers in LCCA application are the shortage of LCC data [185] and the complexity of predicting the real future costs [186]. The first barrier can potentially be overcome by deriving the LCC components from the data generated by evolving building systems – CMMS, BAS, BEMS, etc. With the networks of sophisticated sensors and devices, these systems are generating extensive data involving utility consumption, maintenance work order history, etc. [187], a portion of which can be used for calculating the LCCs. The second barrier can potentially be addressed by the rapid developing Machine Learning techniques. Machine learning is an automated process that extracts patterns from data [188]. In the field of predictive data analytics, machine learning is a method used to devise complex prediction algorithms and models [188,189]. These analytical models enable data analysts to uncover hidden insights, predict future values, and produce reliable, repeatable decisions through learning from historical relationships and trends in the data [190]. The developments of machine learning techniques and more advanced building systems provide building experts with new opportunities to achieve more accurate predictions of the facility LCCs, which enables the assessment of BIM-O&M ROI and determining its value.

4.4. Hazardous waste management

There has been limited BIM related research and studies on some of the O&M topics such as hazardous waste management. Some materials, such as asbestos, were not considered hazardous until years after they had been used in construction. Keeping the record of the material information for existing buildings is critical because, possibly, materials contain certain chemical substances will be required to be removed from the building in the future. In such cases, facility managers, designers, and engineers can use the BIM to learn if these hazardous materials exist in the building and use BIM's capabilities, such as visualization, calculation, and analysis to support the planning of hazardous waste removal. In one relevant study conducted by McArthur [191], a hazardous material database is linked with a BIM to identify asbestos-containing materials and provide relevant information for annual abatement reports.

4.5. ICT asset management

ICT departments have their own management systems and it seems the facility information is not particularly useful for ICT asset management. With the fast development of the ICT industry, the hardware requires update regularly, probably every several years. When hardware asset managers try to optimize the solution for updating the data center, cables, or wireless network, the facility's information can be helpful [192]. For example, when optimizing wireless network hardware arrangement, the material of walls is critical information because the attenuation of Wi-Fi signal varies depending on it. A BIM-based system would be helpful in finding the best solution if it can calculate the signal strength of each space based on the Wi-Fi routers' locations.

4.6. User-centered O&M systems

Currently, many facility managers and field technicians are lacking the knowledge and skills to use existing BIM-enabled facility management tools. As a result, they are hesitant to embrace these new technologies as they found it complicated and not easy to work with. This issue can be addressed by designing user-centered systems that are easy to use. With user-friendly interfaces and intuitive information presentations, BIM-based systems can serve as a support tool rather than a technology burden. Achieving this requires knowledge and techniques of Human-Computer Interaction. Prototype evaluation methods, such as cognitive walkthrough [193], can provide measurements on the user-friendliness aspect of the proposed systems.

4.7. Information logistics for facility analysis models

BIM and the evolving building systems – CMMS, BAS, BEMS, etc. – have the potential to serve as the infrastructure that provides essential data for system diagnostic, forecast, and prescriptive models [187]. However, partly because of the interoperability issues discussed in Section 4.1, data frameworks that can provide integrated and comprehensive building data for FM solutions are yet to be developed. Extensive studies on the BIM-enabled information logistics – right information, at the right time, at the right place, in the right form – are needed to generate associated real-time data by connecting multiple facility databases and creating analysis, diagnostic, predictive, and prescriptive models for smart FM.

5. Conclusion

BIM-enabled facility Operation & Maintenance (O&M) is a new and emerging area of research. This research contributes to the body of knowledge by evaluating and summarizing the current BIM-O&M research and application developments, analyzing research trends, and identifying promising future research directions.

Most of the current BIM-O&M research has focused on energy management. Topics of research areas like emergency management, maintenance and repair also show a steady trend of growing publications. Academic publications on BIM for security and change/relocation management are relatively scarce. Potential BIM applications in hazardous waste management and ICT asset management are suggested in this paper.

Publications studied in this research have shown BIM's potentials in improving facility O&M activities and providing new functionalities for facility managers, such as intuitional 3D visualization, comprehensive analysis, and real-time building information access. Many comprehensive systems are established on the foundation of BIM-based facility database, which provides visualization capability and data accessibility, and they can efficiently acquire, store, and process information and perform analysis to inform facility managers' decisions and automate some of the O&M functions. However, the mass adoption of BIM-O&M systems is still hindered by several challenges – interoperability in the BIM-O&M context, understanding the underlying O&M principles for BIM implementation, and return on investment. A potential starting point to address the interoperability issue in the BIM-O&M context is adopting the National Institute of Standards and Technology (NIST) Cyber-Physical Systems (CPS) Framework. More studies involving surveys are needed to understand the underlying O&M principles for BIM implementation – data requirements, areas of inefficiencies, the process changes. In addition, more studies on the return on investment of the innovative systems are required to justify the value of BIM-O&M applications and an improved Life Cycle Cost Analysis method is critical for such justification.

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References

[1] C. Eastman, P. Teicholz, R. Sacks, K. Liston, B.I.M. Handbook, A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, second ed., John Wiley & Sons, 2011.

[2] National Institute of Building Sciences, United States National Building Information Modeling Standard, Version 3, 2015.

[3] International Organization for Standardization, ISO 29481-1:2016, Building information models – Information delivery manual – Part 1: Methodology and format, 2016.

[4] R. Volk, J. Stengel, F. Schultmann, Building Information Modeling (BIM) for existing buildings — Literature review and future needs, Autom. Constr. 38 (2014) 109–127, https://doi.org/10.1016/j.autcon.2013.10.023.

[5] E. Krygiel, B. Nies, Green BIM: Successful Sustainable Design with Building Information Modeling, John Wiley & Sons, 2008.

[6] B. Hardin, D. McCool, BIM and Construction Management: Proven Tools, Methods, and Workflows, John Wiley & Sons, 2015.

[7] R.S. Weygant, BIM Content Development: Standards, Strategies, and Best Practices, John Wiley & Sons, 2011.

[8] P. Teicholz, IFMA, BIM for Facility Managers, 2013. ISBN: 1118417623, 9781118417621.

[9] A. Akcamete, B. Akinci, J.H. Garrett, Potential utilization of building information models for planning maintenance activities, in: Proceedings of the International Conference on Computing in Civil and Building Engineering, June, 2010, pp. 151-157. ISBN.

[10] B. Becerik-Gerber, K. Kensek, Building information modeling in architecture, engineering, and construction: emerging research directions and trends, J. Professional Issues Eng. Educ. Pract. 136 (3) (2009) 139–147, https://doi.org/10.1061/(ASCE)EI.1943-5541.0000023.

[11] P. Parsanezhad, J. Dimyadi, Effective facility management and operations via a BIM-based integrated information system, CIB Facilities Management Conference, Copenhagen, Denmark, 2014 of Conference, pp. 21–23. http://hdl.handle.net/10652/3034.

[12] D. Ilter, E. Ergen, BIM for building refurbishment and maintenance: current status and research directions, Struct. Survey 33 (3) (2015) 228–256, https://doi.org/10.1108/SS-02-2015-0008.

[13] A. Bosch, L. Volker, A. Koutamanis, BIM in the operations stage: Bottlenecks and implications for owners, Built Environ. Project Asset Manage. 5 (3) (2015) 331–343, https://doi.org/10.1108/BEPAM-03-2014-0017.

[14] R. Santos, A.A. Costa, A. Grilo, Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015, Autom. Constr. (2017), https://doi.org/10.1016/j.autcon.2017.03.005.

[15] IFMA, Definition of facility management, Available from: https://www.ifma.org/about/what-is-facility-management, 2016, (Internet, cited November 6, 2018).

[16] German Facility Management Association (GEFMA), The GEFMA Guidelines (1996 to 2018-02), Available from: http://www.gefma-2018.de/views-detailansicht/shop/, 2018, (Internet, cited Nov. 6, 2018).

[17] E. Pärn, D. Edwards, M. Sing, The building information modelling trajectory in facilities management: a review, Autom. Constr. 75 (2017) 45–55, https://doi.org/10.1016/j.autcon.2016.12.003.

[18] K.O. Roper, R.P. Payant, The Facility Management Handbook, fourth ed., AMACOM Div American Mgmt Assn, 2014. ISBN: 0814432166, 9780814432167.

[19] B.T. Lewis, B.T. Lewis, Facility Manager's Operation and Maintenance Handbook, McGraw-Hill New York, NY, 1999.

[20] B. Atkin, A. Brooks, Total Facility Management, John Wiley & Sons, 2014.

[21] S. Chotipanich, Positioning Facility Management, Facilities 22 (13/14) (2004) 364–372.

[22] E.P. Rondeau, R.K. Brown, P.D. Lapides, Facility Management, John Wiley & Sons, 2012.

[23] K. Roper, L. Borello, International Facility Management, John Wiley & Sons, 2013.

[24] G. Williams, M. May, The Facility Manager's Guide to Information Technology, second ed., 2017. ISBN: 978-1938780004.

[25] IFMA, Operations and Maintenance Benchmarks: International Facility Management Association (IFMA) - September 2017, Available from: http://www.ifma.org/marketplace/bookstore/product-view/operations-and-benchmarks-international-facility-management-association-(ifma)-september-2017, 2017 (Internet, cited Nov. 6, 2018).

[26] V. Maliene, K. Alexander, N. Lepkova, Facilities management development in Europe, Int. J. Environ. Pollut. 35 (2–4) (2008) 171–184.

[27] D. Sapp, Facilities Operations & Maintenance - an Overview, Available from: http://www.wbdg.org/facilities-operations-maintenance, 2018 (Internet, cited Nov. 6, 2018).

[28] C. Mignard, C. Nicolle, Merging BIM and GIS using ontologies application to urban facility management in ACTIVe3D, Comput. Ind. 65 (9) (2014) 1276–1290, https://doi.org/10.1016/j.compind.2014.07.008.

[29] Y. Lu, Z. Wu, R. Chang, Y. Li, Building Information Modeling (BIM) for green buildings: A critical review and future directions, Autom. Constr. 83 (2017) 134–148, https://doi.org/10.1016/j.autcon.2017.08.024.

[30] J.K.W. Wong, J. Zhou, Enhancing environmental sustainability over building life cycles through green BIM: A review, Autom. Constr. 57 (2015) 156–165, https://doi.org/10.1016/j.autcon.2015.06.003.

[31] H.-Y. Chong, C.-Y. Lee, X. Wang, A mixed review of the adoption of Building Information Modelling (BIM) for sustainability, J. Clean. Prod. 142 (2017) 4114–4126, https://doi.org/10.1016/j.jclepro.2016.09.222.

[32] S.S. Bu, G. Shen, C.J. Anumba, A.K.D. Wong, X. Liang, Literature review of green retrofit design for commercial buildings with BIM implication, Smart Sustain. Built. Environ. 4 (2) (2015) 188–214, https://doi.org/10.1108/sasbe-08-2014-0043.

[33] A. GhaffarianHoseini, T.R. Zhang, O. Nwadigo, A. GhaffarianHoseini, N. Naismith, J. Tookey, K. Raahemifar, Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency, Renew. Sustain. Energy Rev. 72 (2017) 935–949, https://doi.org/10.1016/j.rser.2016.12.061.

[34] W. Shou, J. Wang, X. Wang, H.Y. Chong, A comparative review of building information modelling implementation in building and infrastructure industries, Arch. Comput. Methods Eng. 22 (2) (2015) 291–308, https://doi.org/10.1007/s11831-014-9125-9.

[35] A. Bradley, H. Li, R. Lark, S. Dunn, BIM for infrastructure: An overall review and constructor perspective, Autom. Constr. 71 (2016) 139–152, https://doi.org/10.1016/j.autcon.2016.08.019.

[36] M.R. Hallowell, D. Hardison, M. Desvignes, Information technology and safety Integrating empirical safety risk data with building information modeling, sensing, and visualization technologies, Constr. Innov.-England 16 (3) (2016) 323–347, https://doi.org/10.1108/ci-09-2015-0047.

[37] M.J. Skibniewski, Research trends in information technology applications in construction safety engineering and management, Front. Eng. Manage. 1 (3) (2015) 246–259.

[38] W. Shen, Q. Hao, H. Mak, J. Neelamkavil, H. Xie, J. Dickinson, R. Thomas, A. Pardasani, H. Xue, Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review, Adv. Eng. Inform. 24 (2) (2010) 196–207, https://doi.org/10.1016/j.aei.2009.09.001.

[39] Y.Z. Song, X.Y. Wang, Y. Tan, P. Wu, M. Sutrisna, J.C.P. Cheng, K. Hampson, Trends and opportunities of BIM-GIS integration in the architecture, engineering and construction industry: a review from a spatio-temporal statistical perspective, ISPRS Int. J. Geo-Inf. 6 (12) (2017), https://doi.org/10.3390/ijgi6120397.

[40] J.X. Zhu, G. Wright, J. Wang, X.Y. Wang, A critical review of the integration of geographic information system and building information modelling at the data level, ISPRS Int. J. Geo-Inf. 7 (2) (2018), https://doi.org/10.3390/ijgi7020066.

[41] M. Gunduz, U. Isikdag, M. Basaraner, Trending technologies for indoor FM: looking for "Geo" in Information, ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, 2016 of Conference, pp. 277–283. DOI:10.5194/isprs-annals-IV-2-W1-277-2016.

[42] P. Tang, D. Huber, B. Akinci, R. Lipman, A. Lytle, Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques, Autom. Constr. 19 (7) (2010) 829–843, https://doi.org/10.1016/j.autcon.2010.06.007.

[43] R. Sacks, U. Gurevich, P. Shrestha, A review of building information modeling

protocols, guides and standards for large construction clients, J. Inform. Technol. Constr. 21 (2016) 479–503.
[44] W.H. Zhou, H.Y. Qin, J.L. Qiu, H.B. Fan, J.X. Lai, K. Wang, L.X. Wang, Building information modelling review with potential applications in tunnel engineering of China, Roy. Soc. Open Sci. 4 (8) (2017), https://doi.org/10.1098/rsos.170174.
[45] X. Zhao, A scientometric review of global BIM research: Analysis and visualization, Autom. Constr. 80 (2017) 37–47, https://doi.org/10.1016/j.autcon.2017.04.002.
[46] M. Yalcinkaya, V. Singh, Patterns and trends in building information modeling (BIM) research: A latent semantic analysis, Autom. Constr. 59 (2015) 68–80.
[47] Q. He, G. Wang, L. Luo, Q. Shi, J. Xie, X. Meng, Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis, Int. J. Project Manage. 35 (4) (2017) 670–685.
[48] X. Li, P. Wu, G.Q. Shen, X. Wang, Y. Teng, Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach, Autom. Constr. 84 (2017) 195–206.
[49] R. Edirisinghe, K.A. London, P. Kalutara, G. Aranda-Mena, Building information modelling for facility management: are we there yet? Eng. Constr. Arch. Manage. 24 (6) (2017) 1119–1154, https://doi.org/10.1108/ecam-06-2016-0139.
[50] M. Kassem, G. Kelly, N. Dawood, M. Serginson, S. Lockley, BIM in facilities management applications: a case study of a large university complex, Built Environ. Project Asset Manage. 5 (3) (2015) 261–277, https://doi.org/10.1108/BEPAM-02-2014-0011.
[51] R. Miettinen, H. Kerosuo, T. Metsala, S. Paavola, Bridging the life cycle: a case study on facility management infrastructures and uses of BIM, J. Facilities Manage. 16 (1) (2018) 2–16, https://doi.org/10.1108/jfm-04-2017-0017.
[52] S.N. Naghshbandi, BIM for facility management: challenges and research gaps, Civ. Eng. J. 2 (12) (2017) 679–684.
[53] X. Yang, S. Ergan, Design and evaluation of an integrated visualization platform to support corrective maintenance of HVAC problem-related work orders, J. Comput. Civil Eng. 30 (3) (2016), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000510.
[54] Y.C. Lin, Y.C. Su, Developing mobile- and BIM-based integrated visual facility maintenance management system, Sci. World J. 2013 (2013) 124249, , https://doi.org/10.1155/2013/124249.
[55] S. Lee, Ö. Akin, Augmented reality-based computational fieldwork support for equipment operations and maintenance, Autom. Constr. 20 (4) (2011) 338–352, https://doi.org/10.1016/j.autcon.2010.11.004.
[56] R. Liu, R. Issa, 3D visualization of sub-surface pipelines in connection with the building utilities: Integrating GIS and BIM for facility management, in: Computing in Civil Engineering, 2012 of Conference, pp. 341–348. https://doi.org/10.1061/9780784412343.0043.
[57] W. tShen, Q. Hao, Y. Xue, A loosely coupled system integration approach for decision support in facility management and maintenance, Autom. Constr. 25 (2012) 41–48, https://doi.org/10.1016/j.autcon.2012.04.003.
[58] I. Motawa, A. Almarshad, A knowledge-based BIM system for building maintenance, Autom. Constr. 29 (2013) 173–182, https://doi.org/10.1016/j.autcon.2012.09.008.
[59] J. Irizarry, M. Gheisari, G. Williams, K. Roper, Ambient intelligence environments for accessing building information: A healthcare facility management scenario, Facilities 32 (3/4) (2014) 120–138, https://doi.org/10.1108/F-05-2012-0034.
[60] C. Koch, M. Neges, M. König, M. Abramovici, Natural markers for augmented reality-based indoor navigation and facility maintenance, Autom. Constr. 48 (2014) 18–30, https://doi.org/10.1016/j.autcon.2014.08.009.
[61] Y.C. Lin, Y.C. Su, Y.P. Chen, Developing mobile BIM/2D barcode-based automated facility management system, Sci. World J. 2014 (2014) 374735, , https://doi.org/10.1155/2014/374735.
[62] A. Motamedi, A. Hammad, Y. Asen, Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management, Autom. Constr. 43 (2014) 73–83, https://doi.org/10.1016/j.autcon.2014.03.012.
[63] X. Yang, S. Ergan, Leveraging BIM to provide automated support for efficient troubleshooting of HVAC-related problems, J. Comput. Civil Eng. 30 (2) (2016), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000492.
[64] A. Golabchi, M. Akula, V. Kamat, Automated building information modeling for fault detection and diagnostics in commercial HVAC systems, Facilities 34 (3–4) (2016) 233–246, https://doi.org/10.1108/F-06-2014-0050.
[65] F. Shalabi, Y. Turkan, IFC BIM-based facility management approach to optimize data collection for corrective maintenance, J. Perform. Constr. Facil 04016081 (2016).
[66] C.H. Lee, M.H. Tsai, S.C. Kang, A visual tool for accessibility study of pipeline maintenance during design, Visualiz. Eng. 2 (1) (2014), https://doi.org/10.1186/s40327-014-0006-y.
[67] R. Liu, R.R.A. Issa, Survey: common knowledge in BIM for facility maintenance, J. Perform. Constr. Facil (2015), https://doi.org/10.1061/.
[68] J. Zhou, P. Love, J. Matthews, B. Carey, C. Sing, Object-oriented model for life cycle management of electrical instrumentation control projects, Autom. Constr. 49 (2015) 142–151.
[69] U. Isikdag, J. Underwood, G. Aouad, An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes, Adv. Eng. Inf. 22 (4) (2008) 504–519.
[70] T.M. Lawrence, R.T. Watson, M.-C. Boudreau, K. Johnsen, J. Perry, L. Ding, A new paradigm for the design and management of building systems, Energy Build. 51 (2012) 56–63, https://doi.org/10.1016/j.enbuild.2012.04.016.
[71] F. Forns-Samso, T. Laine, B. Hensel, Building information modeling supporting facilities management, in: Proceedings ECPPM Ework and Ebusiness in Architecture, Engineering and Construction, 2012, pp. 51–57. ISBN:9780415621281.
[72] R. Liu, R.R.A. Issa, Automatically Updating Maintenance Information from a BIM Database, in: R.R. Issa, I. Flood (Eds.), Proceedings of the 2012 ASCE International Conference on Computing in Civil Engineering, American Society of Civil Engineers Tech. Council Comput. Inf. Technol. American Soc. Civil Eng. Tech. Council Comput. Inf. Technol. American Soc. Civil Eng., Place of Publication: Reston, VA, USA; Clearwater Beach, FL, USA. Country of Publication: USA., 2012 of Conference, pp. 373–380. https://doi.org/10.1061/9780784412343.0047.
[73] Y. Asen, A. Motamedi, A. Hammad, BIM-based visual analytics approach for facilities management, in: 14th International Conference on Computing in Civil and Building Engineering, Moscow, Russia, 2012 of Conference, pp. 1–8.
[74] W. Wu, X. Yang, Q. Fan, GIS-BIM Based Virtual Facility Energy Assessment (VFEA)–Framework Development and Use Case of California State University, Fresno, Computing in Civil and Building Engineering, 2014 of Conference, pp. 339–346. https://doi.org/10.1061/9780784413616.043.
[75] B. Wu, S. Zhang, Integration of GIS and BIM for Indoor Geovisual Analytics, ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Prague, Czech republic, 2016, pp. 455–458. ISBN.
[76] General Services Administration, BIM Guide For Facility Management Available from: https://www.gsa.gov/cdnstatic/largedocs/BIM_Guide_Series_Facility_Management.pdf, 2011 (Internet, cited Nov. 6, 2018).
[77] N. Bakis, G. Aouad, M. Kagioglou, Towards distributed product data sharing environments - Progress so far and future challenges, Autom. Constr. 16 (5) (2007) 586–595, https://doi.org/10.1016/j.autcon.2006.10.002.
[78] Z. Shen, L. Jiang, An augmented 3D iPad mobile application for communication, collaboration, and learning (CCL) of building MEP systems, Comput. Civ. Eng. 2012 (2012) 204–212.
[79] A. Motamedi, M.M. Soltani, A. Hammad, Localization of RFID-equipped assets during the operation phase of facilities, Adv. Eng. Inf. 27 (4) (2013) 566–579, https://doi.org/10.1016/j.aei.2013.07.001.
[80] A. Papapostolou, H. Chaouchi, RFID-assisted indoor localization and the impact of interference on its performance, J. Network Comput. Appl. 34 (3) (2011) 902–913, https://doi.org/10.1016/j.jnca.2010.04.009.
[81] G. Zimmermann, Y. Lu, G. Lo, Automatic HVAC fault detection and diagnosis system generation based on heat flow models, HVAC&R Res. 18 (1/2) (2012) 112–125, https://doi.org/10.1080/10789669.2011.610427.
[82] Y.-H. Lin, Y.-S. Liu, G. Gao, X.-G. Han, C.-Y. Lai, M. Gu, The IFC-based path planning for 3D indoor spaces, Adv. Eng. Inf. 27 (2) (2013) 189–205, https://doi.org/10.1016/j.aei.2012.10.001.
[83] J. Lee, Y. Jeong, Y.-S. Oh, J.-C. Lee, N. Ahn, J. Lee, S.-H. Yoon, An integrated approach to intelligent urban facilities management for real-time emergency response, Autom. Constr. 30 (2013) 256–264, https://doi.org/10.1016/j.autcon.2012.11.008.
[84] F. Leite, B. Akinci, Reasoning about building systems and content to support vulnerability assessment in building emergencies, J. Comput. Civil Eng. 27 (2) (2013) 118–128, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000214.
[85] N. Li, B. Becerik-Gerber, L. Soibelman, Iterative maximum likelihood estimation algorithm: leveraging building information and sensing infrastructure for localization during emergencies, J. Comput. Civil Eng. 29 (6) (2014) 04014094.
[86] H. Tashakkori, A. Rajabifard, M. Kalantari, A new 3D indoor/outdoor spatial model for indoor emergency response facilitation, Build. Environ. 89 (2015) 170–182, https://doi.org/10.1016/j.buildenv.2015.02.036.
[87] A.Y. Chen, J.C. Chu, TDVRP and BIM integrated approach for in-building emergency rescue routing, J. Comput. Civil Eng. C4015003 (2015).
[88] T. Bloch, R. Sacks, O. Rabinovitch, Interior models of earthquake damaged buildings for search and rescue, Adv. Eng. Inf. 30 (1) (2016) 65–76, https://doi.org/10.1016/j.aei.2015.12.001.
[89] U. Rüppel, K. Schatz, Designing a BIM-based serious game for fire safety evacuation simulations, Adv. Eng. Inf. 25 (4) (2011) 600–611, https://doi.org/10.1016/j.aei.2011.08.001.
[90] P. Abolghasemzadeh, A comprehensive method for environmentally sensitive and behavioral microscopic egress analysis in case of fire in buildings, Saf. Sci. 59 (2013) 1–9.
[91] L.C. Chen, C.H. Wu, T.S. Shen, C.C. Chou, The application of geometric network models and building information models in geospatial environments for fire-fighting simulations, Comput. Environ. Urban Syst. 45 (2014) 1–12, https://doi.org/10.1016/j.compenvurbsys.2014.01.003.
[92] N. Li, B. Becerik-Gerber, B. Krishnamachari, L. Soibelman, A BIM centered indoor localization algorithm to support building fire emergency response operations, Autom. Constr. 42 (2014) 78–89, https://doi.org/10.1016/j.autcon.2014.02.019.
[93] B. Wang, H. Li, Y. Rezgui, A. Bradley, H.N. Ong, BIM based virtual environment for fire emergency evacuation, Scientific World J. 2014 (2014) 589016, , https://doi.org/10.1155/2014/589016.
[94] N. Li, B. Becerik-Gerber, L. Soibelman, B. Krishnamachari, Comparative assessment of an indoor localization framework for building emergency response, Autom. Constr. 57 (2015) 42–54, https://doi.org/10.1016/j.autcon.2015.04.004.
[95] S.-H. Wang, W.-C. Wang, K.-C. Wang, S.-Y. Shih, Applying building information modeling to support fire safety management, Autom. Constr. 59 (2015) 158–167, https://doi.org/10.1016/j.autcon.2015.02.001.
[96] E.M. Wetzel, W.Y. Thabet, Utilizing Six Sigma to develop standard attributes for a Safety for Facilities Management (SFFM) framework, Saf. Sci. 89 (2016) 355–368, https://doi.org/10.1016/j.ssci.2016.07.010.
[97] M.-Y. Cheng, K.-C. Chiu, Y.-M. Hsieh, I.T. Yang, J.-S. Chou, Y.-W. Wu, BIM integrated smart monitoring technique for building fire prevention and disaster relief, Autom. Constr. 84 (2017) 14–30, https://doi.org/10.1016/j.autcon.2017.08.027.
[98] Y.C. Shiau, Y.Y. Tsai, J.Y. Hsiao, C.T. Chang, Development of building fire control and management system in BIM environment, Stud. Inform. Control 22 (1) (2013)

15–24 https://doi.org/10.24846/v22i2y101302.
[99] N. Skandhakumar, F. Salim, J. Reid, R. Drogemuller, E. Dawson, Graph theory based representation of building information models for access control applications, Autom. Constr. 68 (2016) 44–51, https://doi.org/10.1016/j.autcon.2016.04.001.
[100] J.C. Chu, C.-Y. Yeh, Emergency evacuation guidance design for complex building geometries, J. Infrastruct. Syst. 18 (4) (2011) 288–296, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000080.
[101] K. Schatz, J. Schlittenlacher, D. Ullrich, U. Rüppel, W. Ellermeier, Investigating Human Factors in Fire Evacuation: A Serious-Gaming Approach, Pedestrian and Evacuation Dynamics 2012, Springer, 2014, pp. 1113–1121.
[102] E. Mills, Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States, Energ. Effi. 4 (2) (2011) 145–173, https://doi.org/10.1007/s12053-011-9116-8.
[103] W. Sisson, C. van-Aerschot, C. Kornevall, R. Cowe, D. Bridoux, T.B. Bonnaire, J. Fritz, Energy efficiency in buildings: Transforming the market, Available from, 2009 (Internet, cited Nov. 6, 2018).
[104] A. Ahmed, N.E. Korres, J. Ploennigs, H. Elhadi, K. Menzel, Mining building performance data for energy-efficient operation, Adv. Eng. Inf. 25 (2) (2011) 341–354, https://doi.org/10.1016/j.aei.2010.10.002.
[105] T. Crosbie, N. Dawood, S. Dawood, Improving the energy performance of the built environment: The potential of virtual collaborative life cycle tools, Autom. Constr. 20 (2) (2011) 205–216, https://doi.org/10.1016/j.autcon.2010.09.018.
[106] P. Raftery, M. Keane, A. Costa, Calibrating whole building energy models: Detailed case study using hourly measured data, Energy Build. 43 (12) (2011) 3666–3679, https://doi.org/10.1016/j.enbuild.2011.09.039.
[107] H.U. Gokce, K.U. Gokce, Holistic system architecture for energy efficient building operation, Sustain. Cities Soc. 6 (2013) 77–84, https://doi.org/10.1016/j.scs.2012.07.003.
[108] K.-U. Ahn, Y.-J. Kim, C.-S. Park, I. Kim, K. Lee, BIM interface for full vs. semi-automated building energy simulation, Energy Build. 68 (Part B) (2014) 671–678, https://doi.org/10.1016/j.enbuild.2013.08.063.
[109] F.G. Hamza-Lup, M. Maghiar, Web3D graphics enabled through sensor networks for cost-effective assessment and management of energy efficiency in buildings, Graph. Models 88 (2016) 66–74, https://doi.org/10.1016/j.gmod.2016.03.005.
[110] J.T. O'Donnell, T. Maile, C. Rose, N. Mrazovic, E. Morrissey, C. Regnier, K. Parrish, V. Bazjanac, Transforming BIM to BEM: Generation of building geometry for the NASA Ames sustainability base BIM, Available from: http://www.osti.gov/servlets/purl/1168736, 2013 (Internet, cited Nov. 6, 2018).
[111] C.M. Rose, V. Bazjanac, An algorithm to generate space boundaries for building energy simulation, Eng. Comput. 31 (2) (2015) 271–280, https://doi.org/10.1007/s00366-013-0347-5.
[112] A. Oti, E. Kurul, F. Cheung, J. Tah, A framework for the utilization of Building Management System data in building information models for building design and operation, Autom. Constr. 72 (2016) 195–210.
[113] D.-K. Jung, D. Lee, S. Park, Energy operation management for Smart city using 3D building energy information modeling, Int. J. Precision Eng. Manuf. 15 (8) (2014) 1717–1724.
[114] B. Dong, Z. O'Neill, Z. Li, A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics, Autom. Constr. 44 (2014) 197–211, https://doi.org/10.1016/j.autcon.2014.04.007.
[115] M. Marzouk, A. Abdelaty, Monitoring thermal comfort in subways using building information modeling, Energy Build. 84 (2014) 252–257, https://doi.org/10.1016/j.enbuild.2014.08.006.
[116] D. Lee, G. Cha, S. Park, A study on data visualization of embedded sensors for building energy monitoring using BIM, Int. J. Precision Eng. Manuf. 17 (6) (2016) 807–814, https://doi.org/10.1007/s12541-016-0099-4.
[117] G. Gourlis, I. Kovacic, A study on building performance analysis for energy retrofit of existing industrial facilities, Appl. Energy (2016).
[118] W. Yan, M. Clayton, J. Haberl, W. Jeong, J.B. Kim, S. Kota, J.L.B. Alcocer, M. Dixit, Interfacing BIM with Building Thermal and Daylighting Modeling, in: 13th Conference of International Building Performance Simulation Association, Chambery, France, 2013. ISBN.
[119] G. Gourlis, I. Kovacic, Building Information Modelling for analysis of energy efficient industrial buildings–a case study, Renew. Sustain. Energy Rev. 68 (2017) 953–963.
[120] B. Dong, Z. O'Neill, D. Luo, T. Bailey, Development and calibration of an online energy model for campus buildings, Energy Build. 76 (2014) 316–327, https://doi.org/10.1016/j.enbuild.2014.02.064.
[121] E. Corry, P. Pauwels, S. Hu, M. Keane, J. O'Donnell, A performance assessment ontology for the environmental and energy management of buildings, Autom. Constr. 57 (2015) 249–259, https://doi.org/10.1016/j.autcon.2015.05.002.
[122] W. Wu, W. Li, D. Law, W. Na, Improving data center energy efficiency using a cyber-physical systems approach: integration of building information modeling and wireless sensor networks, Procedia Eng. 118 (2015) 1266–1273.
[123] Y. Cao, T. Wang, X. Song, An energy-aware, agent-based maintenance-scheduling framework to improve occupant satisfaction, Autom. Constr. 60 (2015) 49–57.
[124] I. Petri, S. Kubicki, Y. Rezgui, A. Guerriero, H.J. Li, Optimizing energy efficiency in operating built environment assets through building Information Modeling: A Case Study, Energies 10 (2017) (8), https://doi.org/10.3390/en10081167.
[125] A. Costa, M.M. Keane, J.I. Torrens, E. Corry, Building operation and energy performance: Monitoring, analysis and optimisation toolkit, Appl. Energy 101 (2013) 310–316, https://doi.org/10.1016/j.apenergy.2011.10.037.
[126] H.U. Gökçe, K.U. Gökçe, Multi dimensional energy monitoring, analysis and optimization system for energy efficient building operations, Sustain. Cities Soc. 10 (2014) 161–173, https://doi.org/10.1016/j.scs.2013.08.004.
[127] J.R. Dobbs, B.M. Hencey, Model predictive HVAC control with online occupancy model, Energy Build. 82 (2014) 675–684, https://doi.org/10.1016/j.enbuild.2014.07.051.
[128] H.U. Gokce, K.U. Gokce, Integrated system platform for energy efficient building operations, J. Comput. Civil Eng. 28 (6) (2014), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000288.
[129] Z. Alwan, B.J. Gledson, Towards green building performance evaluation using asset information modelling, Built Environ. Project Asset Manage. 5 (3) (2015) 290–303, https://doi.org/10.1108/BEPAM-03-2014-0020.
[130] Z. Yang, A. Ghahramani, B. Becerik-Gerber, Building occupancy diversity and HVAC (heating, ventilation, and air conditioning) system energy efficiency, Energy 109 (2016) 641–649, https://doi.org/10.1016/j.energy.2016.04.099.
[131] C.C. Chou, C.T. Chiang, P.Y. Wu, C.P. Chu, C.Y. Lin, Spatiotemporal analysis and visualization of power consumption data integrated with building information models for energy savings, Resour. Conserv. Recycl. 123 (2017) 219–229, https://doi.org/10.1016/j.resconrec.2016.03.008.
[132] T. Gerrish, K. Ruikar, M. Cook, M. Johnson, M. Phillip, C. Lowry, BIM application to building energy performance visualisation and management: Challenges and potential, Energy Build. 144 (2017) 218–228, https://doi.org/10.1016/j.enbuild.2017.03.032.
[133] K. McGlinn, B. Yuce, H. Wicaksono, S. Howell, Y. Rezgui, Usability evaluation of a web-based tool for supporting holistic building energy management, Autom. Constr. 84 (2017) 154–165, https://doi.org/10.1016/j.autcon.2017.08.033.
[134] W. Natephra, A. Motamedi, N. Yabuki, T. Fukuda, Integrating 4D thermal information with BIM for building envelope thermal performance analysis and thermal comfort evaluation in naturally ventilated environments, Build. Environ. 124 (2017) 194–208, https://doi.org/10.1016/j.buildenv.2017.08.004.
[135] P. De Wilde, The gap between predicted and measured energy performance of buildings: a framework for investigation, Autom. Constr. 41 (2014) 40–49, https://doi.org/10.1016/j.autcon.2014.02.009.
[136] P. Shiel, S. Tarantino, M. Fischer, Parametric analysis of design stage building energy performance simulation models, Energy Build. 172 (2018) 78–93.
[137] T. Reeves, S. Olbina, R.R.A. Issa, Guidelines for using building information modeling for energy analysis of buildings, Buildings 5 (4) (2015) 1361–1388, https://doi.org/10.3390/buildings5041361.
[138] J.C. Zhang, B.C. Seet, T.T. Lie, Building information modelling for smart built environments, Buildings 5 (1) (2015) 100–115, https://doi.org/10.3390/buildings5010100.
[139] A. Abdelalim, W. O'Brien, Z.X. Shi, Data visualization and analysis of energy flow on a multi-zone building scale, Autom. Constr. 84 (2017) 258–273, https://doi.org/10.1016/j.autcon.2017.09.012.
[140] N. Dawood, H. Dawood, S. Rodriguez-Trejo, M. Crilly, Visualising urban energy use: the use of LiDAR and remote sensing data in urban energy planning, Visualiz. Eng. 5 (1) (2017), https://doi.org/10.1186/s40327-017-0060-3.
[141] S. Habibi, Micro-climatization and real-time digitalization effects on energy efficiency based on user behavior, Build. Environ. 114 (2017) 410–428, https://doi.org/10.1016/j.buildenv.2016.12.039.
[142] M. Schmidt, M.V. Moreno, A. Schülke, K. Macek, K. Mařík, A.G. Pastor, Optimizing legacy building operation: The evolution into data-driven predictive cyber-physical systems, Energy Build. 148 (2017) 257–279, https://doi.org/10.1016/j.enbuild.2017.05.002.
[143] J. Ploennigs, A. Ahmed, B. Hensel, P. Stack, K. Menzel, Virtual sensors for estimation of energy consumption and thermal comfort in buildings with underfloor heating, Adv. Eng. Inf. 25 (4) (2011) 688–698, https://doi.org/10.1016/j.aei.2011.07.004.
[144] P. Yung, X.Y. Wang, A 6D CAD model for the automatic assessment of building sustainability, Int. J. Adv. Rob. Syst. 11 (2014), https://doi.org/10.5772/58446.
[145] K. Kensek, Y. Ding, T. Longcore, Green building and biodiversity: facilitating bird friendly design with building information models, J. Green Build. 11 (2) (2016) 116–130, https://doi.org/10.3992/jgb.11.2.116.1.
[146] S. Pinheiro, R. Wimmer, J. O'Donnell, S. Muhic, V. Bazjanac, T. Maile, J. Frisch, C. van Treeck, MVD based information exchange between BIM and building energy performance simulation, Autom. Constr. 90 (2018) 91–103, https://doi.org/10.1016/j.autcon.2018.02.009.
[147] V. Voropajev, Change management—A key integrative function of PM in transition economies, Int. J. Project Manage. 16 (1) (1998) 15–19, https://doi.org/10.1016/S0263-7863(97)00010-0.
[148] P. Pittet, C. Cruz, C. Nicolle, An ontology change management approach for facility management, Comput. Ind. 65 (9) (2014) 1301–1315, https://doi.org/10.1016/j.compind.2014.07.006.
[149] C. Merschbrock, A.K. Lassen, T. Tollnes, B.E. Munkvold, Serious games as a virtual training ground for relocation to a new healthcare facility, Facilities 34 (13–14) (2016) 788–808, https://doi.org/10.1108/F-02-2015-0008.
[150] S. Porter, T. Tan, T. Tan, G. West, Breaking into BIM: Performing static and dynamic security analysis with the aid of BIM, Autom. Constr. 40 (2014) 84–95, https://doi.org/10.1016/j.autcon.2013.12.002.
[151] N. Skandhakumar, F. Salim, J. Reid, E. Dawson, Physical Access Control Administration using Building Information Models, Cyberspace Safety and Security, Springer, 2012, pp. 236–250.
[152] E.W. Dijkstra, A note on two problems in connexion with graphs, Numer. Math. 1 (1) (1959) 269–271, https://doi.org/10.1007/BF01386390.
[153] Y.C. Lin, Y.C. Su, Developing mobile- and BIM-based integrated visual facility maintenance management system, Sci. World J. (2013), https://doi.org/10.1155/2013/124249.
[154] M.R. Halfawy, Municipal information models and federated software architecture for implementing integrated infrastructure management environments, Autom.

Constr. 19 (4) (2010) 433–446, https://doi.org/10.1016/j.autcon.2009.11.013.
[155] E. Pärn, D. Edwards, Conceptualising the FinDD API plug-in: A study of BIM-FM integration, Autom. Constr. 80 (2017) 11–21.
[156] M. Yalcinkaya, V. Singh, Building information modeling (BIM) for facilities management–literature review and future needs, in: IFIP International Conference on Product Lifecycle Management, Springer, 2014 of Conference, pp. 1–10. https://doi.org/10.1007/978-3-662-45937-9_1.
[157] NIST, Cyber-Physical Systems, Available from: http://www.nist.gov/el/cyber-physical-systems, 2017 (Internet, cited Nov. 6, 2018).
[158] NIST, Framework for Cyber-Physical Systems, Available from: https://pages.nist.gov/cpspwg/, 2016 (Internet, cited Nov. 6, 2018).
[159] F. Xia, L.T. Yang, L. Wang, A. Vinel, Internet of things, Int. J. Commun Syst. 25 (9) (2012) 1101, https://doi.org/10.1002/dac.2417.
[160] Z.M. Fadlullah, M.M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, Y. Nozaki, Toward intelligent machine-to-machine communications in smart grid, in: IEEE Communications Magazine, vol. 49, 2011. ISBN:0163-6804.
[161] J. Bruner, Industrial Internet, "O'Reilly Media, Inc.", 2013. ISBN: 1449365914.
[162] K. Su, J. Li, H. Fu, Smart city and the applications, Electronics, Communications and Control (ICECC), in: 2011 International Conference on, IEEE, 2011, pp. 1028–1031. ISBN:1457703211.
[163] A. Aurigi, Making the Digital City: The Early Shaping of Urban Internet Space, Routledge, 2016.
[164] CPS Public Working Group, CPS PWG Cyber-Physical Systems (CPS) Framework Release 1.0, Available from: pages.nist.gov/cpspwg/, 2018 (Internet, cited Nov. 6, 2018).
[165] NIST, IES-City Framework, Available from: https://s3.amazonaws.com/nist-sgcps/smartcityframework/files/ies-city_framework/IES-CityFrameworkdraft_20180207.pdf, 2018 (Internet, cited November 6, 2018).
[166] S. Donkers, H. Ledoux, J.Q. Zhao, J. Stoter, Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings, Trans. Gis 20 (4) (2016) 547–569, https://doi.org/10.1111/tgis.12162.
[167] S.K. Jusuf, B. Mousseau, G. Godfroid, J.H.V. Soh, Path to an integrated modelling between IFC and CityGML for neighborhood scale modelling, Urban Sci. 1 (3) (2017) 25, https://doi.org/10.3390/urbansci1030025.
[168] S.K. Jusuf, B. Mousseau, G. Godfroid, V.S.J. Hui, Integrated modeling of CityGML and IFC for city/neighborhood development for urban microclimates analysis, in: J.L. Scartezzini (Ed.), Cisbat 2017 International Conference Future Buildings & Districts - Energy Efficiency from Nano to Urban Scale, vol. 122, 2017, pp. 145–150. DOI: 10.1016/j.egypro.2017.07.329.
[169] P. Pishdad-Bozorgi, X. Gao, C. Eastman, A.P. Self, Planning and developing facility management-enabled building information model (FM-enabled BIM), Autom. Constr. 87 (2018) 22–38, https://doi.org/10.1016/j.autcon.2017.12.004.
[170] Pennsylvania State University, BIM Planning Guide for Facility Owners (Version 2), Available from: http://bim.psu.edu/Owner/Resources/contact_info.aspx, (2013) (Internet, cited Nov. 6, 2018).
[171] B. Becerik-Gerber, F. Jazizadeh, N. Li, G. Calis, Application areas and data requirements for BIM-enabled facilities management, J. Constr. Eng. Manage.-Asce 138 (3) (2012) 431–442, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000433.
[172] M. Gheisari, S. Goodman, J. Schmidt, G. Williams, J. Irizarry, Exploring BIM and mobile augmented reality use in facilities management, in: Proceedings of the Construction Research Congress, 2014 of Conference, pp. 1941–1950. https://doi.org/10.1061/9780784413517.198.
[173] A. Sattenini, S. Azhar, J. Thuston, Preparing a building information model for facility maintenance and management, in: 28th International Symposium on Automation and Robotics in Construction, Seoul, South Korea, 2011, pp. 144–149. ISBN: 9781510804296.
[174] H. Smyth, A.M. Anvuur, I. Kusuma, Integrated solutions for total asset management through "RIVANS", Built Environ. Project Asset Manage. 7 (1) (2017) 5–18, https://doi.org/10.1108/BEPAM-07-2015-0034.
[175] R. Liu, R.R.A. Issa, Survey: Common Knowledge in BIM for Facility Maintenance, J. Perform. Constr. Facil 30 (3) (2016), https://doi.org/10.1061/(ASCE)CF.1943-5509.0000778.
[176] G. Mayo, R.R.A. Issa, Nongeometric building information needs assessment for facilities management, J. Manage. Eng. 32 (3) (2016), https://doi.org/10.1061/(ASCE)ME.1943-5479.0000414.
[177] X. Yang, S. Ergan, BIM for FM: information requirements to support HVAC-related corrective maintenance, J. Archit. Eng. 23 (4) (2017), https://doi.org/10.1061/(asce)ae.1943-5568.0000272.
[178] G. Carbonari, S. Stravoravdis, C. Gausden, Improving FM task efficiency through BIM: a proposal for BIM implementation, J. Corporate Real Estate 20 (1) (2018) 4–15, https://doi.org/10.1108/jcre-01-2017-0001.
[179] Q.C. Lu, L. Chen, S. Lee, X.J. Zhao, Activity theory-based analysis of BIM implementation in building O & M and first response, Autom. Constr. 85 (2018) 317–332, https://doi.org/10.1016/j.autcon.2017.10.017.
[180] International Organization for Standardization, The International Organization for Standardization, Available from: http://www.iso.org/home.html, 2018 (Internet, cited Nov. 6, 2018).
[181] buildingSMART, Model View Definition Summary, Available from: http://www.buildingsmart-tech.org/specifications/ifc-view-definition, 2018 (Internet, cited November 6, 2018).
[182] buildingSMART, Information Delivery Manuals, Available from: iug.buildingsmart.org/idms, 2018 (Internet, cited Nov. 6, 2018).
[183] S. Fuller, Life-cycle cost analysis (LCCA), Available from: https://www.wbdg.org/resources/life-cycle-cost-analysis-lcca, 2010 (Internet, cited Nov. 6, 2018).
[184] ASTM, Standard practice for measuring life-cycle costs of buildings and building systems, ASTM E917-17, 2017. DOI: 10.1520/E0917-17.
[185] N. Bakis, R. Amaratunga, M. Kagioglou, G. Aouad, An integrated environment for life cycle costing in construction, Available from: http://usir.salford.ac.uk/9970/1/300_Bakis_N_AN_INTEGRATED_ENVIRONMENT_FOR.pdf, 2003 (Internet, cited Nov. 6, 2018).
[186] D.J. Ferry, R. Flanagan, Life cycle costing: a radical approach, construction industry, Res. Inform. Assoc. London ISBN (1991) 0860173224.
[187] X. Gao, S. Tang, P. Pishdad-Bozorgi, D. Shelden, Foundational Research in Integrated Building Internet of Things (IoT) Data Standards, Available from: https://cdait.gatech.edu/sites/default/files/georgia_tech_cdait_research_report_on_integrated_building_-_iot_data_standards_september_2018_final.pdf, 2018 (Internet, cited Nov. 6, 2018).
[188] J.D. Kelleher, B.M. Namee, A. D'Arcy, Fundamentals of Machine Learning for Predictive Data Analytics: Algorithms, Worked Examples, and Case Studies, MIT Press, 2015 ISBN: 9780262029445.
[189] T.M. Mitchell, Machine Learning, McGraw-Hill, 1997 ISBN: 9780071154673.
[190] SAS, Machine Learning: What it is & why it matters, Available from: https://www.sas.com/it_it/insights/analytics/machine-learning.html, 2018 (Internet, cited Nov. 6, 2018).
[191] J.J. McArthur, A Building Information Management (BIM) Framework and Supporting Case Study for Existing Building Operations, Maintenan. Sustain., Procedia Eng. 118 (2015) 1104–1111, https://doi.org/10.1016/j.proeng.2015.08.450.
[192] R. Tomasi, F. Sottile, C. Pastrone, M.M.R. Mozumdar, A. Osello, L. Lavagno, Leveraging BIM Interoperability for UWB-Based WSN Planning, IEEE Sens. J. 15 (10) (2015) 5988–5996, https://doi.org/10.1109/JSEN.2015.2451736.
[193] P.G. Polson, C. Lewis, J. Rieman, C. Wharton, Cognitive walkthroughs: a method for theory-based evaluation of user interfaces, Int. J. Man Mach. Stud. 36 (5) (1992) 741–773, https://doi.org/10.1016/0020-7373(92)90039-N.