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Review

A Systematic Review of the Extent to Which BIM Is Integrated into Operation and Maintenance

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Abstract: Although a considerable amount of research has addressed the use of building information modelling (BIM) in facilities management (FM) within the past years, there is limited systematic review on investigating the potentials of BIM within the operation and maintenance (O&M) life cycle phase. Yet, this phase could account for approximately 60% of the total life cycle costs of assets. The purpose of this paper is to conduct a systematic literature review on the application of BIM in the O&M phase to identify current research trends, research gaps and future directions. This study achieves the aforementioned purpose by adopting the preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P). It employs qualitative and quantitative techniques to analyse the articles from a combination of three multi-disciplinary research databases, namely—Scopus, Web of Science and Engineering Village, which also comprises Compendex, InSpec, GeoRef and GeoBase sub-databases. After an in-depth review of 196 selected journal articles, this study systemically presents: (1) bibliometric analyses of the literature in BIM and O&M; (2) research patterns and trends; (3) drivers and barriers to BIM–O&M integration; and (4) research gaps mapped into a standard project management lifecycle to guide future research directions. The content analysis reveals that BIM has mainly been integrated under seven functions: information management (IM), advanced technology (AT), maintenance and asset management (MAM), indoor management (IM), performance assessment (PA), visualisation (V), and lean management (LM). Findings of the study reveal that the UK, USA and China are the top ranked countries with regards to research outputs on BIM–O&M integrations. The majority of BIM integrations within O&M falls under the information management function, whereas the least research output was recorded under lean management. In addition, the majority of studies focused on institutional and infrastructure facility types, but residential, industrial and commercial buildings were underrepresented, despite their disproportionate physical dominance within most societies. Findings also show that potential drivers and barriers for BIM integrations within O&M can be classified into three main categories—technical, organisational, and legal/contractual. It is then concluded that the application of BIM within O&M is still emerging, which further emphasises the need for more studies that address value realization in the context of BIM in O&M, with particular focus on the specific O&M principles for different building types.

Keywords: construction; building information modelling (BIM); operations and maintenance (O&M); drivers; barriers; asset management (AM)

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1. Introduction

Building information modelling (BIM) is changing the way facilities and infrastructure are conceived and managed. It has provided designers and builders with opportunities for successful project delivery, at a higher quality and a lower cost. BIM applications in design and construction have outgrown the research phase and are now deployed and implemented in different construction projects worldwide [1]. However, building owners and other construction project stakeholders usually focus on the initial investments from the design-to-construction phases because they occur within a relatively shorter time than other phases of the building life cycle. While the design-to-construction phases typically account for 2–5 years, the operations and maintenance (O&M) phase usually takes up to 20 years and even beyond, which makes it crucial to the realisation of a good return on investment (ROI) [2]. This indicates that the ongoing costs of building operations and maintenance far outweigh the capital investment on construction. This implies that there is a possibility for huge cost savings with BIM in O&M [3]. The sustainability of physical assets is highly dependent on their reliability and maintainability, especially in the O&M phase due to their high of return of investment (ROI). According to the National Institute of Standards and Technology (NIST), poor integration and interoperability results in as much as USD 15.8 billion worth of lost opportunity [4], with most of the losses (more than 60% on average) incurred by facility owners at the O&M phase. However, limited studies within the existing body of knowledge have explored the application of BIM during the O&M phase [5]. This indeed depicts the fact that the full potentials of BIM within the O&M phases are yet to be wholly harnessed [6,7]. This is perhaps why some more recent studies have begun to address BIM enhancements in space management, asset management and sustainability [8,9]. The studies mostly adjudged that BIM initiatives can provide enhancements beyond construction, for example, for maintenance decision making [10], energy utilisation [5], building commissioning and contingency response activities.

However, even though BIM in O&M has been acknowledged as far back as 2010, its adoption and utilisation during the O&M phase remains slow, owing to several justifications. Firstly, the absence of clear information needs that support the use of BIM in the O&M phase makes it difficult to support the integration. Facility managers do not have the BIM requirements in place to address their needs in the O&M phase [11]. Thus, when the integration takes place, these requirements are either missing or unclear. FM teams do not normally use BIM data models, either because these models do not include the required operational needs or because FM teams lack understanding of how to transfer information from BIM models to other systems. The reason behind that is the undefined principles for BIM with respect to people, processes and systems [12]. It is recommended that business owners and facility managers should engage at the early stages of building life cycles in order to optimise all aspects of design, construction, O&M and decommissioning [11]. Secondly, the compatibility between BIM and the different systems used during the building life cycle (e.g., CMMS, CAFM and BAS) is complex. This often leads to laborious manual interventions, which are time-consuming and critical to the success of the adoption process. Thirdly, since assessing the performance of the integration is critical to its success, the absence of key metrics that can actually assess the integration in the O&M phase, when it takes place, can further hinder the process. Many researchers have reported methodologies for assessing and monitoring building performance [13–15]. However, none have identified key performance indicators (KPI) for BIM in the O&M phase, although few authors, such as Eadie et.al. [16], investigated general KPIs for BIM, but were not focused on the O&M stage. Due to the aforementioned reasons, BIM integrations within the O&M phase remain slow and their applications are limited. This necessitated a state-of-the-art review that can capture the in-depth justifications behind the slow adoption for BIM in O&M. Furthermore, these aspects created a need to investigate the current BIM capabilities in supporting facility O&M by examining how each O&M activity can be leveraged by BIM and to what extent they actually support the O&M phase of the building life cycle. Although the information may be available at some points, questions around how to derive the usefulness of these data within BIM for O&M applications remain unanswered.

The aim of this research is to use a systematic approach to provide valuable insights regarding the current literature surrounding BIM in the O&M phase. It identifies, analyses and summarizes functions of these integrations with an in-depth analysis of the O&M scope. Initially, a detailed description of the methodology adopted for the systematic literature review (SLR) is presented, after which the key findings will be addressed under two distinct sections. The former section presents a bibliometric analysis of the search results, while the latter section provides a comprehensive content analysis of BIM–O&M integrations. Furthermore, the drivers and barriers hindering BIM–O&M adoption are then brought to the fore. Subsequently, the study identifies gaps in knowledge and then maps them against a standard project management lifecycle to guide future research directions for academics and industry professionals. Finally, the study presents concluding remarks to summarize the main findings and contributions to knowledge.

2. Research Methodology

The literature review methodology deployed for this study is based on preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P). Systematic literature review (SLR) is often argued to provide the "*most reliable and comprehensive statement about what works*" [17]. The methodology ensures an effective description of the analytic approach of the review. A comprehensive protocol adapted from Moher et al. and Okoli [18–21] is followed and illustrated in this section.

2.1. Review Questions

The fundamental aim of the current study is to systematically review the existing literature on BIM applications, with keen interests in the extent to which such concepts are embedded into the O&M phase. Therefore, the review questions were formulated to be:

1. What is the current state of the art of BIM applications and to what extent are they integrated into the O&M phase?
2. What are the possible drivers and barriers to adopting BIM applications in O&M?
3. What are the emergent research gaps in the area of BIM–O&M integrations?

2.2. Inclusion and Exclusion Criteria

The core characteristics of SLRs are their justifications for each of the captured primary articles, which are often demonstrated via inclusion and exclusion criteria. Therefore, the inclusion criteria for this SLR are:

- All available articles on BIM integration within the O&M phase of construction and infrastructure domains;
- All available articles that address drivers and barriers to BIM–O&M integration;
- Only journal papers were included due to their more rigorous peer-review process, higher reliability and validity [22];
- This SLR was not constrained by a time frame so as to ensure a more encompassing approach to information tracking and data capturing;
- Articles written in English.

2.3. Search Strategy

The three databases chosen as the main sources of information for this SLR were Scopus, Web of Science and Engineering Village, although Engineering Village also comprises additional engineering-specific databases, namely; InSpec, Compendex, Geobase and GeoRef. The selection of these databases was due to their efficient, easy and advanced searching options, as well as their reliable and comprehensive academic information in the specified area of this research. The methodology consists of five main stages, namely: scoping, identification, screening, eligibility and final records. In the first stage, the databases and research questions were formulated. In the second stage, the advanced keywords searching option was used with the following phrases (("Building information model *" OR "building model *" OR "BIM") AND ("operation and maintenance" OR "asset management" OR "facility * management" OR "maintenance information management" OR "maintenance management *" OR "computeri * maintenance management *")). The total number of returned results were 669 articles which was further refined based on the inclusion criteria. A total of 413 articles were duplicated, and the remaining 256 were further screened in stage 3. In the third stage, the unrelated articles were excluded through title and abstract assessments. The penultimate stage entailed establishing the eligibility of the remaining

218 articles based on full-text availability, which in turn informed the 196 articles included in the fifth and final stage. Figure 1 provides a stepwise description of the research strategy deployed in this study.

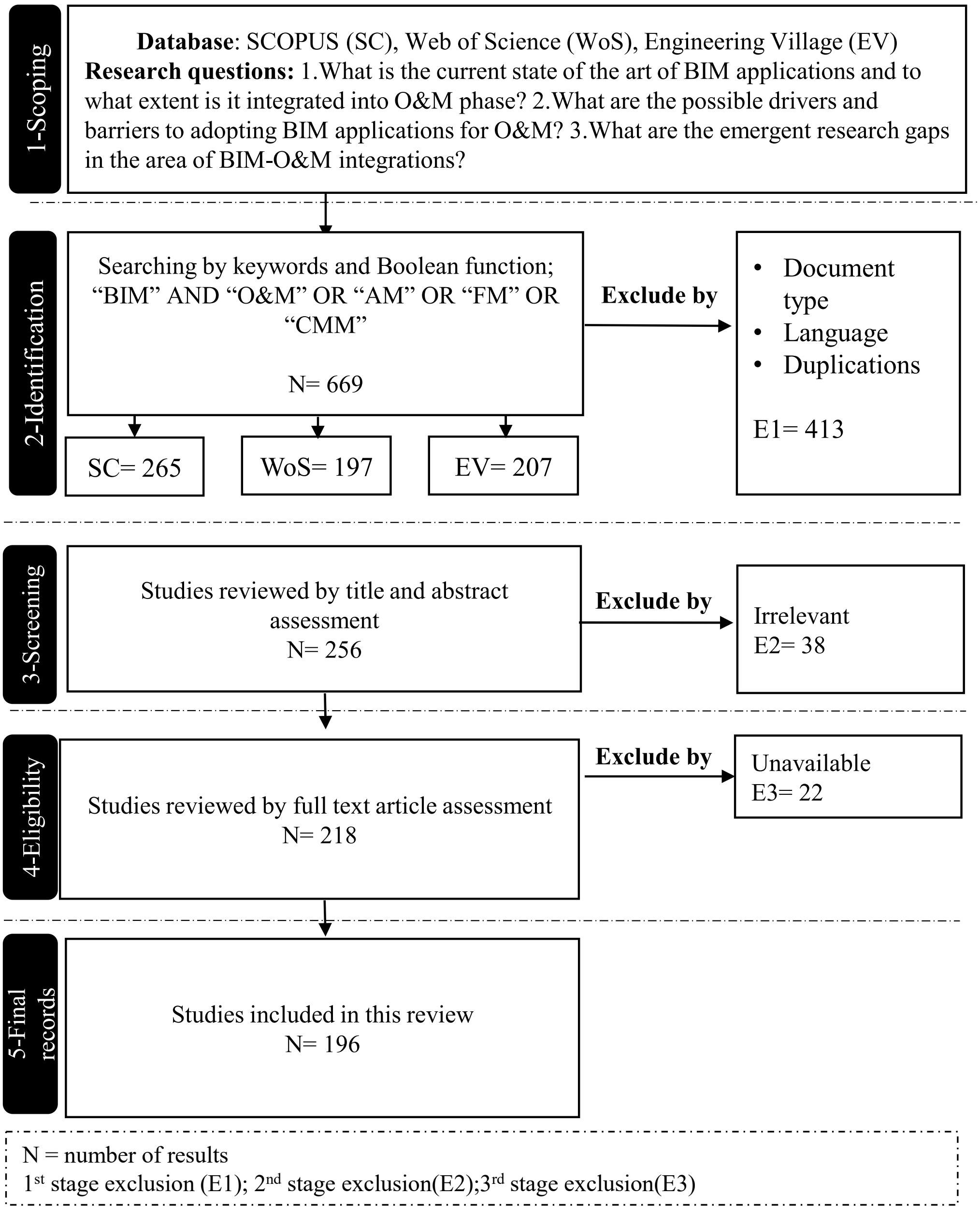

Figure 1. Flow chart for research methodology (PRISMA).

2.4. Screening

Although the inclusion and exclusion criteria defined earlier would have aided the definition of the primary articles, further assessment of relevance is also necessary to ensure maximum representativeness. As defined by PRISMA-P guidelines, screening entails brief scanning of titles and abstracts, but the full text of an article may also be examined if ambiguity is suspected. The following activities were implemented during the screening process:

1. Search results were filtered based on inclusion and exclusion criteria;
2. Duplicated articles were removed;
3. Each article title and, if required, its abstract/full assessment were reviewed to further establish relevance;

4. Related articles were then saved to a reference management platform (in this case Mendeley Desktop version);
5. The total number of included articles was recorded.

2.5. Data Extraction

The data extraction methods were a combination of qualitative and quantitative tools. The content analysis of this study draws on the methodology adopted in other review articles, such as [23,24]. This study analyses and categorises the existing research on BIM integrations within O&M by conducting quantitative and qualitative analyses. The bibliometric analysis in this review aims to provide the quantitative analysis element of the study by using statistical methods to analyse trends of academic publications to evaluate the existing research performance as well as understand the patterns [23,24]. The content analysis, on the other hand, provides the qualitative element by deriving themes based on the articles [23,24]. The study identifies seven main thematic functions from the content analysis which were drawn from the journal papers used in the systematic review."

2.6. Quality Evaluation

The main forms of quality assessment implemented here were through the choice of search databases and the restriction of the included primary articles to just journals due to their higher reliabilities and validity resulting from their rigorous peer-review processes [22].

2.7. Synthesis

In this SLR, the text of each article was reviewed, and all relevant sections were critically examined in order to establish themes, sub-themes, relations, classifications and comparisons.

3. Findings and Discussions

3.1. Bibliometric Analysis

The bibliometric analysis results show that the first study addressing BIM in O&M was published in 2010, which coincides with the emergence of the concept of whole life/asset management strategies through the release of asset management standards, such as Publicly Available Specification 55 (PAS 55) in 2008/2009. In addition, Figure 2 shows growth in the number of publications on BIM applications within the O&M phases of construction and infrastructure over the last decade from just four articles in 2013 to 36 in 2019. Interestingly, 82% of these studies were published in the last five years, indicating that integrating BIM with O&M is still an emerging area of research.

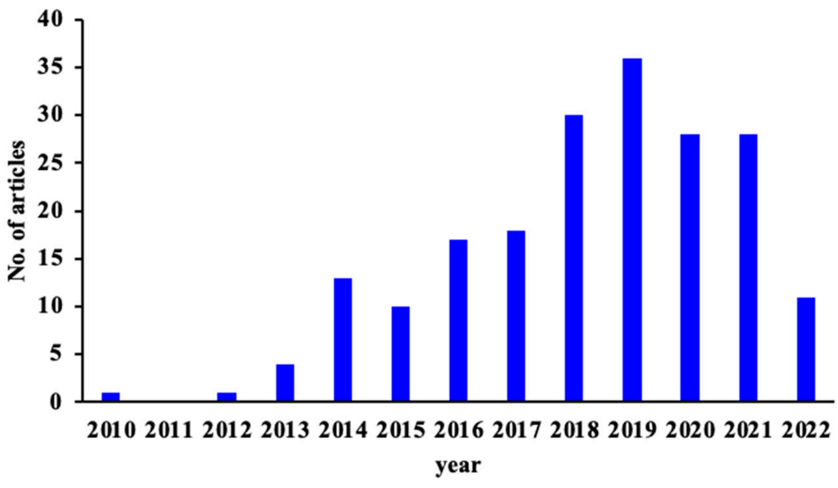

Figure 2. Annual distribution of articles.

Based on the search strategy and method (with outputs spanning over 13 years), the highest volume of publications focusing on BIM implementations in O&M were recorded in the "Automation in Construction" journal, with 30 papers of the total 196 articles selected for the study. This was followed by 19 articles from the "Facilities" journal and nine papers from the "Journal of Information Technology in Construction". These top three journals account for almost 32% of the total number of publications. Moreover, the following three journals, namely "Built Environment Project and Asset Management", "Buildings" and "Journal of Facilities Management", published seven, six and six articles, respectively. In addition, "International Journal of Building Pathology and Adaptation", "Journal of Building Engineering", "Journal of Computing in Civil Engineering", "Journal of Management in Engineering" and "Journal of Performance of Constructed Facilities" published five, six and four articles, respectively, as depicted by Figure 3. The remaining journals' publication rates vary between one and three articles spread across 13 years (i.e., between 2010 and 2022). The bibliometric analysis further revealed that the largest number of publications originated from the United Kingdom (37), United States (36), China (16), Italy (16) and Canada (15), as shown in Figure 4. It does not come as a surprise that the UK and USA have the highest proportion of journal articles related to BIM applications in O&M. This could be because BIM was established in the USA and the UK government's construction strategy advocates the adopting of BIM across all construction projects [25].

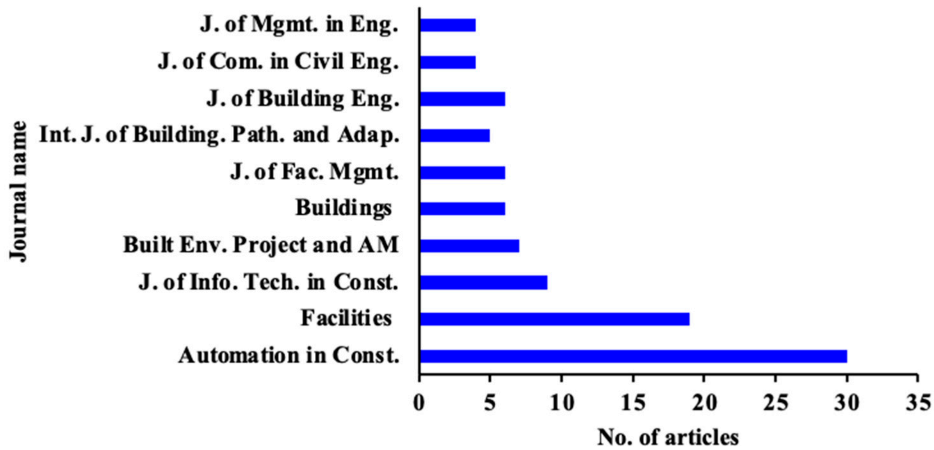

Figure 3. Top 10 journals with the highest research outputs.

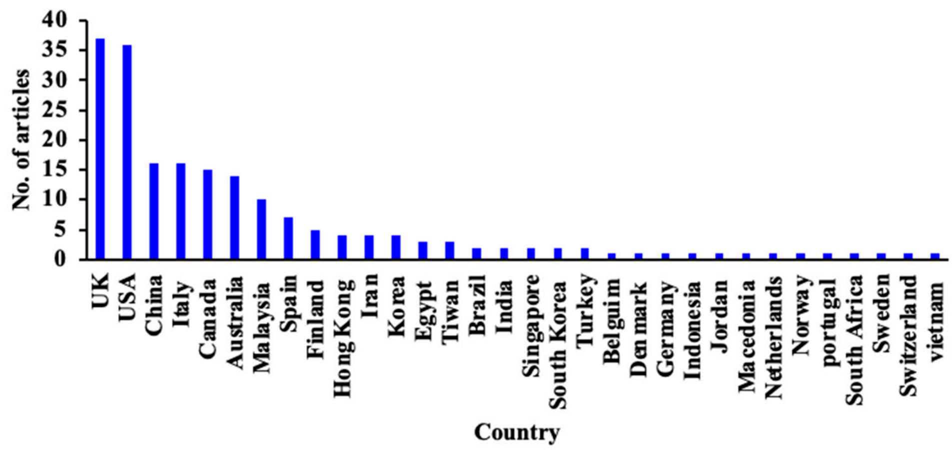

Figure 4. Number of publications per country.

3.2. Originality

Twenty of the 196 retained articles were literature reviews that focused on the integration of BIM in O&M. However, 15 of the 20 literature review articles addressed general BIM integration activities but were not specific to O&M. The areas covered include BIM for general FM and asset management [26,27], information technology [28–30], safety in facilities management [31], benefits and challenges for general FM practices with BIM [32–34] and interoperability [23]. These articles neither placed any emphasis on the actual use of BIM during the O&M phase nor addressed any specific features of maintenance. Thus, these reviews are limited in their discussions of BIM applications in the premise of O&M and they are very generic in their scopes, which clearly highlights that research gaps around the areas of improving BIM integration within O&M remain ambiguous.

Only the remaining five literature review articles [11,24,35–37] focused on reviewing the literature surrounding BIM in the O&M phase of construction and infrastructure, as presented in Table 1. According to Table 1, most of the studies regard FM as a unified set of functions rather than distinguishing specific activities. Despite the keyword phrases listed, very few studies have actually reviewed a specific maintenance feature or focused on an identified O&M scope. In fact, only two studies actually emphasized maintenance-related features. Marmo et al. [37] reviewed previous case studies that focused on the integration of BIM and O&M in order to develop a building performance assessment model to support maintenance planning and decision making along with the identification of clear information requirements, including their sources for each case study. However, their review did not identify the specific O&M features for the considered case studies. Xinghua and Pishdad-Bozorgi [24] classified BIM role into five main facets and proposed an interesting classification theme for maintenance and repairs, including information accessibility, augmented visualization, decision making support, root cause failure and maintainability analyses. Their review included 150 publications, but only 14 studies were explicitly devoted to BIM and maintenance. For this reason, one of the cornerstones of this SLR was to investigate what efforts have been directed towards identifying instances of BIM integration within O&M and to what level these integrations focused on specific O&M systems rather than general FM practices. To the best of the authors' knowledge, there has been minimal emphasis on BIM applications with specific focuses on O&M systems. There are nearly no comprehensive reviews addressing the clear, specific and in-depth analysis of maintenance features and requirements with BIM. We, therefore, aim to close this gap through this review, as it provides detailed insights about the current efforts of BIM within the O&M phase, research trends and specific functions as well as sub-functions, which result in clearly identified research gaps.

Table 1. A summary of previous review studies with focus on BIM–O&M.

Ref.	Key Words Used	Focus	Findings and Research Gaps	O&M Features Discussed?
[32]	Revit, BIM, FM, O&M, (COBie), dynamic maintenance, fragmentation, interoperability	BIM-FM key issues and challenges	16 key issues identified and then grouped into four categories	no
[33]	Not discussed	Benefits and challenges in BIM-FM	Three drivers, four barriers, and requirements for utilising BIM for FM are not clearly understood	no
[26]	"FM" OR "AM"	FM and AM with BIM	Interoperability	no
[28]	"BIM" and "O&M"	Image-based technologies	Gaps include efficiency, accuracy, quality, practicability and economy	no
[27]	BIM AND FM or construction AND issues AND integration	BIM-AM	BIM information delivery issues are classified into four categories.	no
[37]	'BIM', 'Information Management', 'FM', 'O&M', 'CMMS', 'CAFM', 'case study', 'BPA'	(BIM–O&M) integration case studies	Performance information model (PIM). Stakeholders engagement is not realized and high adoption costs for BIM–FM integration	Yes
[31]	Not discussed	Safety in FM	Lack of safety-related information in FM	no

Table 1. *Cont.*

Ref.	Key Words Used	Focus	Findings and Research Gaps	O&M Features Discussed?
[29]	"Big Data adoption (BD)" + "Construction" + "factors" + ...	Big data adoption	Factors that drive BD in BIM in construction	no
[11]	BIM and FM, maintenance, operations, lifecycle	BIM in FM	Gaps were identified in a conceptual framework between five stages of the innovation diffusion theory.	no
[30]	COBie	Cobie-centric	Nine key benefits and 24 key issues	no
[24]	"BIM","O&M", "emergency management", and "energy management"	BIM to improve O&M	Interoperability with the need of more surveys to understand O&M requirements and ROI value	Yes
[35]	Not discussed	BIM and maintenance management	Not discussed	no
[36]	Not discussed	BIM in O&M	Interoperability issues; AR; enhanced performance measurement; and enriched training and competence.	no
[23]	"BIM", "FM", "O&M", "AM"	Interoperability	Gaps in interoperability BIM and integrating BIM and mixed reality	no
[34]	Not discussed	Challenges for BIM in FM	Lack of best practices and guidelines, interoperability and training	no
[38]	"BIM", "FM", "O&M". "Interoperability", "Data Exchange", "Information Management", "BIM Lifecycle Management", "BIM-FM Integration".	BIM for FM in large capital projects	BIM–FM integration field is predominantly technological and process-oriented, with less focus on organisational aspects	no
[39]	"BIM" AND "FM"	BIM-enabled FM	the knowledge structure of BIM-FM was divided into five significant clusters	no
[40]	Not discussed	sustainable and effective building maintenance	introduced seven strategies to improve maintenance work procedures	Yes
[41]	"BIM", "digital twin", smart buildings, FM, AM, O&M, energy management, emergency management, space management	the applications of disruptive technologies for FM	A starting point for FM includes developing Digital Twin platforms by integrating BIM and IoT technologies	no
[42]	"BIM level", "FM", "IoT", "sensors", "open cloud platform", "semantic web", "digital twin", "integration", "IFC"	Standards to integrate BIM and IoT.	Existing and emerging open standards can help strengthen the EBIM concept	Yes

4. Content Analysis

In this stage, the 196 papers selected were rigorously reviewed. Each of the 176 primary articles (excluding the 20 review articles) was examined by identifying the aim of the research, year of publication, research methods deployed in the study, research questions or gaps addressed, main findings, critical overview of the strength(s) and limitation(s) of the studies, main function under which BIM was integrated with O&M, sub-function(s) corresponding to such integration(s), whether a specific maintenance scope was addressed or discussed, future recommendations, and whether the study highlights any possible barriers or obstacles to BIM adoption. In addition, the examination process identified all the different building types and infrastructures where BIM was integrated with O&M. In other words, this review paper critically examines the current literature to answer the research questions: (1) what is the current state of the art of BIM applications and to what extent are they integrated into the O&M phases? (2) What are the possible drivers and barriers to adopting BIM applications in O&M? (3) What are the emergent research gaps in the area of BIM–O&M integrations? In order to adequately answer these questions, the following additional sub-questions were posed to help guide the investigation process of the review: What are the main functions in integrating BIM with O&M? How are they defined? What are the sub-functions of these integrations? What types of building projects were studied, and under what functions were they targeted? Did the study focus on any maintenance-specific features? If so, what were they? What are the possible barriers to hinder such adoption?

4.1. Main Functions of Integrating BIM with O&M

Based on the content analysis, the articles were examined to identify themes and sub-themes based on their area of focus and scope within O&M. The analysis identified seven main functions for BIM integration with O&M. These functions are: information management (IM); advanced technology management (ATM); maintenance and asset management (MAM); indoor management (InM); performance assessment management (PAM); visualization management (VM); and lean management (LM). Additionally, an additional category was created to accommodate articles that more or less discuss BIM benefits and challenges within the broader field of FM. The seven identified thematic functions overlap and can be divided into: "what processes are managed", "what in (these) processes is managed" (IM, VM), and "how (these) processes are managed" (LM). In other words, the seven thematic functions can be grouped into processes, functions and methods. The processes category includes all the activities and actions performed in order to achieve the integration of BIM within O&M. It includes advanced technology management (ATM); maintenance and asset management (MAM); indoor management (InM); and performance assessment management (PAM). The functions category deals with the specific scope of improving and optimising these processes, such as information management (IM) and visualization management (VM). Finally, the methods category includes the means of managing as well as conducting the functions and processes, such as lean management (LM). The classification of articles was based on a set of questions that fulfill each purpose or function, as shown in Table 2.

Table 2. BIM functions classifications.

Function	Classification Criteria
IM	What information is needed? How is it classified? What are the relations? How are are they linked with software and databases? How are the associated data is examined?
ATM	How do technological advancements link BIM with FM? What technologies/tools/methods are needed?
VM	What is a better way to visualize data? How can data accessibility be improved? How is information seen by end-users?
MAM	How is the maintenance data defined and collected? What maintenance features are studied? What level of maintenance management was explored? Does it consider the whole life cycle of assets? Does it explore how AM information adds value to BIM?
InM	Does the study focus on indoor occupants/satisfaction or comfort? Is the activity indoor-based?
PAM	How was the performance of a certain subject assessed? What behaviors need to be captured?
LM	What are the value added benefits of BIM? How are they defined? Are lean principles involved?

Additionally, Figure 5 shows the percentage of publications under each function. One the one hand, there are indications that most research has been conducted on IM (38%), followed by ATM (23%) and then MAM (17%). On the other hand, the studies focusing on LM are relatively few with only three journal articles in total. Nevertheless, the classifications of the studies also revealed that among the selected articles, few studies discussed or emphasised a specific maintenance-related feature, activity, specification or purpose. This implies that almost 26% explored actual maintenance activities with BIM involvement, which further highlights that this is still a growing research area.

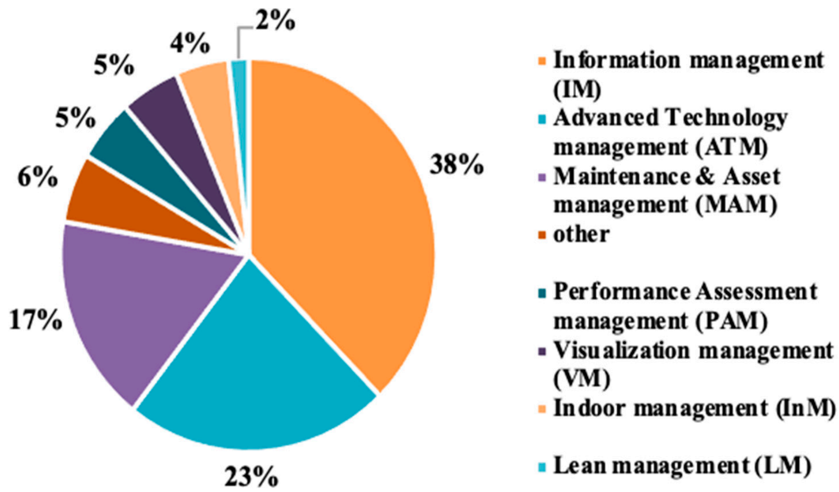

Figure 5. Percentage of BIM–O&M publications in each function.

4.2. Overview of Methods and Tools

The reviewed studies deployed various types of methods and tools within their innovative systems or proposed frameworks. Most of them used a mixture of approaches, for instance, case studies and programming or document analysis or simulation. However, the content analysis revealed 10 main methods from the literature, namely: case studies (CS), programming (P), expert-based methods (with data collection via survey, questionnaire, focus group and interviews), literature review (LR), document analysis (DA), technological methods (including videos, camera, sensors, etc.), simulation (SM), experiment (E), theories (grounded theory, technology-organisation-environment theory, activity theory) and reliability-based tools (fault tree analysis, failure mode and effect analysis FMEA, work breakdown structure WBS). Figure 6 provides details of the distribution of articles against methods, where it can be seen that majority of articles used case studies (93 articles), then programming (86 articles) and expert-based methods (63 articles).

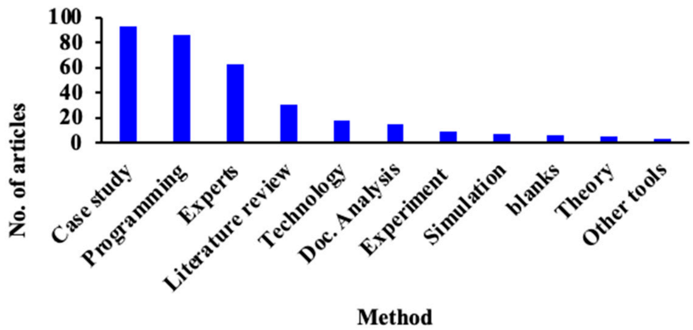

Figure 6. Number of articles deploying each method.

Since almost 36% of the reviewed studies used expert-based methods with data collection via surveys (SV), questionnaires (Q), focus groups (F) and interviews (N), this review further investigated these methods by identifying: (1) the purpose of using each method; (2) profile of participants; (3) sample size; (4) scope; and (5) main BIM–O&M function considered, as can be seen in Table 3. Upon completing the analysis in Table 3, Figure 7 further shows that 41% of these methods included interviews, 19% used a mixture of tools, 16% applied surveys, 14% used focus groups and 10% used questionnaires. This emphasizes that interviews as well as expert judgment and opinions form a great source of information in the area of BIM–O&M research. Figure 8 presents the distributions of the average sample sizes that were considered reliable and sufficient with each method within the reviewed studies [43,44].

Table 3. Summary of expert-based tools, profile of participants, sample size and scope.

Ref.	Method	Aim	Profile	Size	Scope	Function
[45]	N, SV	To identify critical activities, actors and drivers for BIM in O&M	Academics, BIM & FM professionals, government	14 N, 32 SV	Survey based	
[46]	N	To understand current practice for performing FM and information requirements	FM personnel, management, logistics, procurement, O&M	27	-	IM
[47]	Q	To highlight participant's attributes and context of the case study	Surveyors, engineers, architects, and an expert from the industry	36	-	V
[32]	Q	Identify source of previously identified key issues from the literature	FM personnel with 0–30 years of experience	57	Literature based	
[48]	SV	Overview of MEP maintainability problems	Industry practitioners	-	Industry professionals, project based	M
[49]	SV	To observe current O&M processes and identify information needs	FM management, personnel	31	Project based	PA
[16]	SV	Analysis of BIM implementation throughout the UK construction project lifecycle	BIM adopters	92	Country based	other
[50]	N	Verify information about maintenance execution and investigate the root causes	Turnaround maintenance practitioners, production, vendor	8	Project based	LM
[51]	N	To address maintenance management problems and the use of emerging technologies	Engineers only	8	Country-organisation based	M
[52]	N	To understand information and design requirements	Operations department, experts in FM	22	Country-organisation based	IM
[53]	N	To understand what type of elevators needed and how maintenance activities are managed.	Building manager, technical staff and the administrative personnel	-	Country-organisation based	M
[54]	N, WS	Identify OIR (organisational info req.) And AIR asset info req.	Senior management, O&M and the AM teams	-	Organisation based	IM
[55]	F, SV	Visual COBie internal validity of the implementation	FM personnel	40	Project based	V
[44]	Q, N	To prioritize the required BIM information to support FM systems	FM personnel with less than 5 and more than 15 years of experience	191 SV	Literature based	IM
[56]	Q, SV	To measure the implications of BIM-Lean approaches	BIM and lean process practitioners	32	Literature based	LM
[57]	F, SV	To determine the gaps, challenges and benefits for a full BIM to FM integration	Members of the OPP, members of the Computer Integrated Construction (CIC) Research Group, a contractor, vendors	-	Project-organisation based	IM
[58]	F	Identify and review functions and requirements of the API development for BIM in FM		7 F	Object based	IM
[59]	SV, F	To measure user satisfaction	More than 10 years of experience in FM and building performance	1013 SV, 9 F	System based (HVAC)	INM

Table 3. *Cont.*

Ref.	Method	Aim	Profile	Size	Scope	Function
[60]	N, SV	To examine FM functions and processes and BIM benefits	Facility owners, maintenance manager, the facilities project manager, senior facilities coordinators, and senior facilities specialists	24	System based	IM
[61]	N	To obtain detailed information regarding the current practice for occupant feedback	Building managers with +5 years of experience	22	Case study based	INM
[62]	N	To gather data on aspects that impact BIM business value in the business processes of the asset owners	Advanced level of knowledge and understanding of BIM in	-	Case study based	IM
[12]	N	Knowledge about BIM in the operations stage in the Netherlands	Dutch client forum. Public real estate and infrastructure owners and operators, service providers and contractors	21	Country based	IM
[27]	N	To obtain perspectives on BIM-based asset integration.	Practitioners involved in BIM asset integration	10	System based (M&E)	-
[63]	F	To address value of BIM in O&M, as well as the frequency of use of the product information categories.	FM from AEC industry	22	Case study based	IM
[64]	F, N	To develop the EIR draft content and then make suggestions for improvements	Bifm operational readiness steering group	8 F, 7 N	Project based	IM
[65]	F	To explore the meaning of the available data, and generate themes, compared against theoretical concepts.	Australian Facility Management Association (FMA) BIM-FM Portfolio Group, hereafter referred to as FBPG	10	Country based	IM
[66]	N	To understand current processes, available technology to support these processes, and information requirements	Operations department	9	Project based	IM
[13]	N	To understand current maintenance regime	Environmental Sustainability Co-ordinator, Technical Surveyors and Property Services Managers	5	Project based	PA
[67]	N, WS	To understand challenges in BIM implementation on transportation infrastructure projects	Owners and contractors involved in highway maintenance	60	System based	AT
[68]	SV	To collect perspectives from industry practitioners to understand the requirements of facility managers and the type of maintainability problems	Engineers, contractors, facility managers, civil engineers and software developers	63	Survey based	IM
[69]	SV	To explore the current status of BIM application and technologies used	FM	80	Survey based	AT
[37]	N, F	To understand the information needed to control performances, their systems in use and communication tools	Engineers, doctors, nurses, and a chemist, all experts of maintenance	17	System based (surgery room)	-
[43]	N	To capture the requirements of the framework and the CDE	FM, design, engineering and specialized software engineering organisations	15	Projects based	AT

Table 3. *Cont.*

Ref.	Method	Aim	Profile	Size	Scope	Function
[70]	F	To gather input from facilities operators regarding the information they typically need for each FM task	FM experts, with at least 10 years of experience, refrigeration engineers, director of operations, facility supervisors, building engineers, building operators or foremen, a facility engineer, HVAC mechanics	40	System based (HVAC)	M
[71]	Q	To ascertain the level of perceived inefficiencies of operational tasks	Executive and senior managers, operations	752	Survey based	IM
[72]	N	To map the possibilities of BIM to operate as a platform for FM	Experts with BIM, but nobody had experience in using BIM in FM. Senior researchers, top management, etc.	27	Case study based	AT
[73]	N	To investigate the foundation of a well-equipped digital FM system for future O&M	FM personnel, the contractor's project manager and design manager, the client's project managers, architects and consulting engineers	52	Country-case study based	other
[74]	N	To gather data around the information tools they use, and the needs and impediments of the BIM implementation in the FM.	-	11	Country-case study based	IM
[75]	N	To collect views on the relative importance and potential for building performance evaluation using BIM methods	Architects, quantity surveyors, mechanical engineers and construction management practitioners.	20	Interview based	PA
[76]	N	To refine the developed Lean-Agile process	Interviews with the FM/end-user	-	Case studies based	LM
[77]	N	To obtain further insights into the process of developing and delivering FM enabled BIM	Members of the institute's facilities department, the BIM team, a contractor, an architect, a mechanical engineer and software and consulting company	11	Case study based	IM
[78]	N	To collect data on BIM in FM in the project	Designers, an engineer, a BIM expert, a HVAC design coordinator and a coordinator of maintenance manual.	11	Project—country based	IM
[79]	N	To gather information about maintenance management problems	Professional engineers working in high-rise IBS	8	Project—country based	IM
[80]	F, N	To gather information about types of data that could be used to improve BAM decision-making	Interviews with AM professionals, BAM stakeholders	-	System based (shower room)	M
[81]	N	To understand the challenges of BIM implementation in AM	Advanced level of knowledge and understanding of BIM in AM	-	Interview	AM
[82]	F	To refine and validate the process model	AM industry experts from the Constructing Excellence Asset Management theme group	-	Project	IM
[83]	N	To obtain detailed information relating to assets data	Participants are senior personnel of Granlund Manager, Building Automation, Digital Property Services and Innovation And Development	9	Interview based	AM
[84]	F, N	To evaluate and validate the developed taxonomy	Five years' experience in BIM projects; an expert in BIM applications, and a mechanical or electrical engineer.	8	Interviews based	IM

Table 3. *Cont.*

Ref.	Method	Aim	Profile	Size	Scope	Function
[30]	Q	To ascertain their views over these identified benefits and issues	Architect, Developer, Engineer (MEP), BIM manager and FM Project manager	86	Literature-questionnaire based	-
[9]	F, N	To define the link between classes in different ontologies	Five years' experience in BIM and/or asset management and a mechanical or electrical engineer.	8	Experts based	AT
[14]	F	To determine the leading factors for BIM competency	Architects/engineers, contractors, owners, consultants, and academics with experience in BIM competency in FM	21	Expert-based	PA
[85]	Q	To describe how three leading Québec public organisations exploit BIM to digitize their AM journey	Professionals involved in BIM implementation, management and technical staff	3	Project-country based	AM
[86]	F	Validating the conceptual AHP	Managers, team leaders, engineers, and architects	8	Experts based	M
[87]	Q	To determine critical factors for BIM-FM integration	A civil engineer, quantity surveyor, building services engineer, architect and facilities manager	165	Questionnaire based	IM
[88]	F, Q	Understanding the current state of facilities information management in BIM-based projects	BIM practitioners in the UK, British Institute of Facilities Management, with 1–20 years of experience	112 Q-12 F	Questionnaire –literature based	IM
[89]	N	Demonstration of the current maintenance management system	Engineers	8	Interview-country based	IM
[90]	SV	To understand information requirements for O&M data	FM staff members	12	Survey-country based	IM
[91]	N	To review the current FM practices for heritage buildings	Construction professionals in BIM & heritage buildings	5	country specific	AT
[92]	F	To validate the defects obtained by reviewing the literature	FM, construction managers and academics	15	project specific	M
[93]	F	To obtain more in-depth information of how BIM in O&M frameworks in the industry	Experts in BIM and O&M	15	country specific	IM
[94]	SV	To gather data around the effective implementation of BIM for maintenance management	Facility managers, construction managers, quantity surveyors, architects, and engineers	126	country specific	IM
[95]	SV	To review the ultization processes of the BIM-FM platform	A BIM manager, BIM seniors and a BIM engineer	4	interviews	IM
[96]	SV	To investigate the maintenance management practices of a high-rise IBS building	Clients/maintenance contractors	8	country specific	IM

Notes: Surveys = SV, Questionnaire = Q, Focus group = F, Interviews = N.

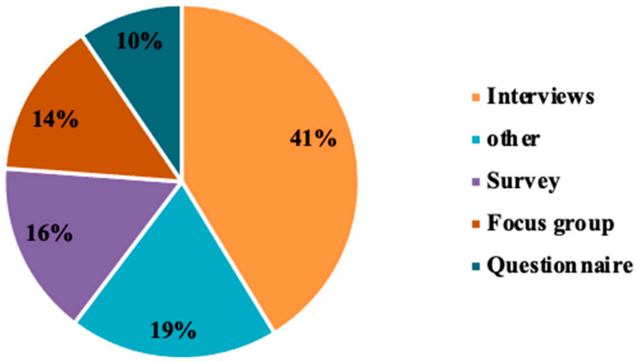

Figure 7. Percentage of each expert-based tool.

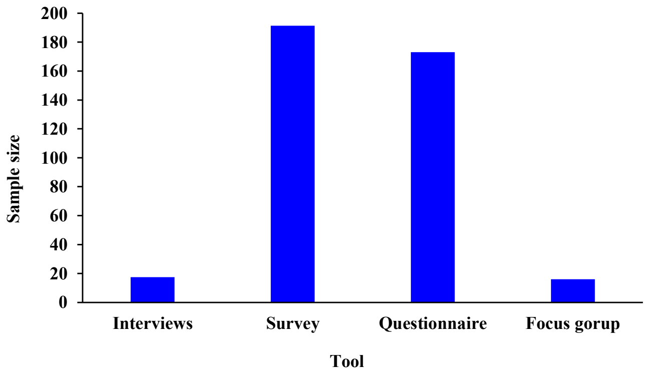

Figure 8. Average sample size for expert-based tools.

Additionally, Table 4 presents a matrix of the types of people-based tools that have been deployed under different integration functions. According to Table 4, the majority of the tools fall within the information management function, as it is one of the most crucial elements of asset management and BIM. Information is used to build asset registers and without accurate asset registers, there cannot be maintenance optimisation. Table 4 shows an opportunity to optimise O&M with BIM applications, especially in indoor management and visualisation.

Table 4. Number of studies using expert-based tools within individual functions.

	Function							
Tool	**ATM**	**IM**	**InM**	**LM**	**MAM**	**PAM**	**VM**	**Other**
N	5	14	1	2	5	2		1
SV	1	8	1	1	1	1	1	1
Q		3	-	1	1		1	-
F	1	9	-		4	1	1	-

Notes: information management (IM); advanced technology management (ATM); maintenance and asset management (MAM); indoor management (InM); performance assessment management (PAM); visualization management (VM); lean management (LM).

4.3. Overview of Building and Facility Types

Figure 9 presents a distribution of the different types of buildings and infrastructure that have been considered by earlier studies, so as to better understand where research efforts have been concentrated as well as the underrepresented areas. For better comparisons, the buildings have been grouped into the following five main categories [20]. Residential buildings include different housing types, such as apartments, town houses or duplexes. Commercial buildings are generally used by businesses to sell products and services to clients and consumers. Examples are shopping malls, grocery stores and general stores. Industrial plants are mainly used to produce, store and distribute goods or services, such as manufacturing companies. Infrastructure indicates the physical structures required for the operation of certain enterprises, especially roads, bridges, HVAC systems and plumping systems. Institutional buildings refer to any type of building that fulfils the role of contributing to healthcare, education, recreation or public works. Examples include hospitals, universities and government buildings. As can be seen from Figure 10, the majority of the studies (44%) have focussed on institutional buildings, such as universities and hospitals, while 11% investigated how to enhance O&M with BIM in infrastructures and 9% explored the commercial sector. This indicates that further efforts can be given to explore BIM in improving the O&M phase in commercial, residential and industrial buildings.

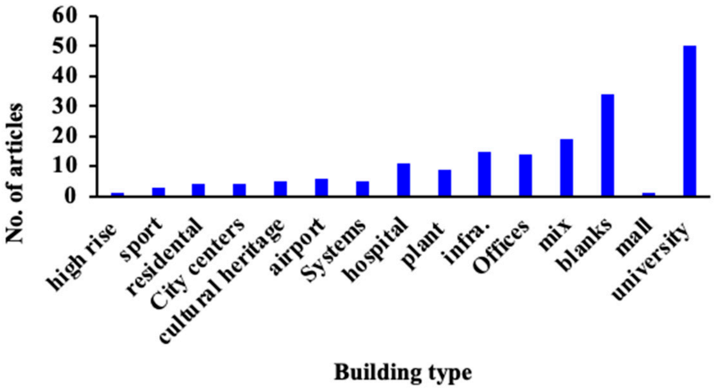

Figure 9. Number of studies in each facility type.

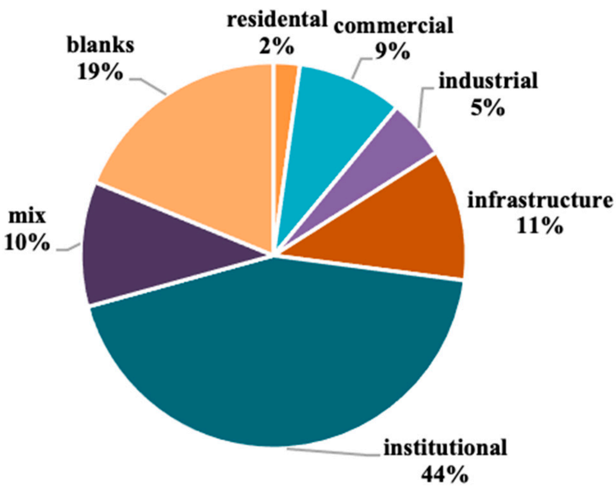

Figure 10. Percentage of studies on BIM–O&M in each building type.

In addition, the matrix in Table 5 shows what functions of BIM in O&M were explored with respect to building types, in which it is evident that information management (IM) recorded the largest portion of publications especially in institutional buildings, but that relatively low focus had been given to visualization management (VM) and lean management (LM). Another interesting finding is the lack of maintenance-focused BIM applications in residential and industrial facilities. The distribution also depicts a generally low research consideration for commercial facilities and infrastructure. Therefore, this matrix clearly highlights knowledge gaps regarding the classification of buildings covered and provides valuable means by which practical improvements can be implemented.

Table 5. Number of studies in each facility type in each function.

	Function							
Building Type	**ATM**	**IM**	**InM**	**LM**	**MAM**	**PAM**	**VM**	**Other**
Commercial	3	3	3	-	6	1	-	-
Infrastructure	2	7	1	-	4	2	3	1
Institutional	22	32	4	1	14	3	3	4
Industrial	4	3	-	2	-	-	-	-
Residential	1	1	-	-	-	1	-	-
Mix	2	8	-	-	2	1	2	-

5. Overview of Existing Publications on BIM in the O&M Phase

Among the 196 articles retained (excluding the 20 review articles), 176 studies addressed different contributions in the field of operation and maintenance. These contributions have been classified into seven functions, as explained earlier in Section 4. In this Section, an overview of the contents of the individual studies within each of the seven functions will be provided, while further discussing their associated sub-functions to enhance the comprehensiveness of this SLR.

5.1. Information Management

Table 1 in Appendix A elaborates that the most notable research efforts of BIM applications within the O&M phase through information management can be classified under four areas—information requirements; data handling/exchange; failure analysis; and fault detection and diagnosis and O&M support.

5.1.1. Information Requirements

It is essential to have accurate and comprehensive data for FM teams to support effective decision making during the operations and maintenance phase. Many efforts have been devoted towards the definition of information requirements that can better drive the integration of BIM into O&M FM. Several researchers have focused on identifying clear information requirements for building handover processes. For instance, Thabet and Lucas [97] developed a seven-step handover framework to identify required data based on owner requirements for educational institutions, allowing clear data tracking throughout the integration process. However, further grouping of the proposed data would enhance the quality of data integration. Sadeghi et al. [98] used their framework to classify information requirements into five categories: location, specifications, warranty, maintenance instructions and construction specifications. However, the proposed model has been criticized for its lack of flexibility and its requirements for further customization and validations. Other classifications include those rendered by East et al. [99] whereby information was classified as either geometric-related or asset-related. Authors, such as Mayo and Issa [63], have focused on non-geometric information needs through the Delphi method but have not adequately considered the later O&M phase, as these identified information needs lack sufficient details in terms of which O&M systems/activities they relate to, and how to manage these needs once they are identified within the O&M systems. Nguyen et al. [90] claimed that the design, suppliers and BIM-FM teams are all key to the successful handover process. Additionally, the diversity of organisational needs were considered by [54,66,100]. Csavka et al. [66] presented a vibrant case study with numerous functions of FM practices and categorised information in alignment with organisational constructs, available technology, project artifacts and owner requirements. They [52] further categorised the level of information required in another study into: (1) maintenance personnel; (2) building management system; and (3) asset management. Hosseini et al. [65] proposed a typology matrix that shows: (1) ownership types of assets; (2) service delivery models offered; and (3) type of data and information. However, the finding of the study also needs to be tested within empirical settings to further validate applicability in real-life projects. Other efforts focused on addressing information needs for transportation [60], education [46,57,77,101] and cultural heritage [64,102]. In addition, information requirements and clients' needs to improve asset management were investigated to enhance the BIM integration [62,84,103–105]. Most of these studies did not report back the benefits of such integrations on maintenance. Although these studies have focused on BIM within O&M, the justifications for quantifiable improvements, such as maintenance costs or maintenance scheduling, remain to be fully explored.

5.1.2. Data Handling

Other studies addressed data accessibility and handling issues which are also crucial for effective integration with BIM [82,106–110]. Lucas et al. [111,112] proposed a seven-model function to support facilities management in healthcare that allows better storage, retrieval and management of data. Interestingly, one of very few studies applied reliability analysis techniques, such as FMEA and FTA, to enhance the gathering of failure data. However, the study did not explore the later O&M phase as it did not show how learning from failures or how the collected data can relate to the optimisation of maintenance. Matarneh et al. [111] enhanced data handling by a reduction in manual data entry time through the integration of a computerised maintenance management system (CMMS) and computer-aided facility management system (CAFM). Alnaggar and Pitt [113] improved data flow by proposing a conceptual model based on applying basic project management theories. Yet, the full collaboration of policy makers especially towards standardising COBie is still lacking. Other attempts targeted the improvement of FM data collection by developing plug-in applications [58].

5.1.3. Failure Analysis and Fault Detection and Diagnosis (FDD)

The application of the principles of learning from failures (LFF) [114–116] to capture crucial maintenance activities and building deterioration characteristics has also gained traction over the past years. Regarding information management, Ismail et al. [89] integrated BIM with FDD and proposed an algorithm that reduces design specification defects for industrialized building systems (IBS) in Malaysia. Yang and Ergan improved the troubleshooting of HVAC systems issues by proposing a model process that generates a work order context, identifies applicable causes for reported HVAC problems and refines relevant causes. It is important to state that as valuable as these research contributions are to general BIM knowledge enhancement, they were more focused on how information was managed and integrated rather than exploring the required methods for capturing such data for FDD.

5.1.4. O&M Support

Several research endeavours around IM have considered how to safely and cost-effectively optimise O&M practices within BIM premises. Some of such notable studies include Ismail et al. [117] who identified five key features of maintenance management systems: defect assessment (DA), BIM maintenance assessing (BMA), expert defect diagnosis (EDD), remedial measures (RM) and database control centre (DCC). Shalabi and Turkanet [118] also investigated how to minimize the lead time of collecting high-quality data for corrective maintenance through IFC-BIM environments. Zhan et al. [119] improved the inspection and repair process through three key players—inspectors that routinely assess the actual conditions of assets through condition monitoring approaches, managers that make the ultimate decisions on resources and repairmen that execute the stipulated maintenance plans on site. However, despite the criticality of the identified job functions and their associated processes to the success of maintenance optimisation, the magnitude of improvements that can be realized regarding time and costs remains unclear. Additionally, the framework proposed by Zhan et al. [119] to improve information flow in the inspection-repair process through image classification algorithms is considered impractical, unless it allowed users to access the BIM knowledge repository from different computers over the internet. In addition, the framework has difficulties in recognizing similar images since any two identical microwaves would be difficult to differentiate according to the proposed algorithm. Liu and Issa [68] attempted to address the knowledge gap between design phase and FM by proposing a general facility maintenance knowledge database with an emphasis on the maintainability assessment at different life cycle phases and decreasing the number of maintenance interventions. However, no responses were obtained from professionals, such as structural engineers, fabricators or mechanical, electrical and plumbing (MEP) equipment manufacturers. Other areas of interests included location [120] and space management [121]. Safety in O&M was another emerging research aspect [122] with only two publications in 2018. Efforts to dynamically connect BIM-based H&S management system during O&M with programmed maintenance cycles for historical industrial plants was explored in [123]. Furthermore, safety by design to improve the O&M phase was studied in [124].

Among the selected articles under this function, very few publications have focused on specific O&M systems rather than general FM practices. It was found that most of the studies showed how to extract or link the data from a certain management system. However, this review reveals that very few studies addressed the fundamental problem of what data need to be acquired from specific O&M activities instead of general FM tasks prior to proposing a methodology for integration. In addition, most studies addressed information management efforts for general maintenance practices or general FM tasks; work on identifying information requirements for specific O&M tasks was scare. Examples can be seen in the study by Villa et al. [123], who specifically examined working from heights but without reference to O&M, unlike the study by Lee et al. [110] and Shalabi et al. [118] who considered in-depth corrective maintenance needs and Chen et al. [125] who focused on tunnel cleaning activities. There remains a lack of holistic guidance on how to collect data from O&M activities, what data to acquire, who should be responsible, which O&M activities are most critical and what resultant value is added to the integration with BIM.

5.2. Advanced Technology Management

It is vital to bridge the knowledge gap and the disconnection between the identified information requirements and their seamless integration across systems. The use of advanced technologies and techniques to allow for this integration through data processing and exchange between systems is extensively discussed within the literature, as summarised in Table 2 in Appendix A.

5.2.1. Augmented Reality (AR)

One of the earliest efforts are addressed by Lee and Akin [126] in 2010, who proposed a computational framework through the application of augmented reality (AR) to support computer-aided O&M. However, the proposed methodology only works for pre-defined physical markers, which limits its functionality in real-world applications. Additionally, the application is limited to the scenarios used in the experiment, which in turn necessitates further validations to better ascertain its robustness and proficiency. Gheisari and Irizarry [69] further advocated that locating building components and 3D visualisation are the most valuable aspects of BIM, as this was seen to fit with AR. In the same vein, Chen et al. [127] introduced a collaborative framework between BIM and AR through video streaming, thereby enabling current location of users, room identification, visualisation and interaction with surroundings in real time.

However, the application was not practical for outdoor environments or during power outages and suffered from quality resolution issues. This limitation was also found in the study by Williams et al. [128], whose application of AR with BIM was threatened by a loss of data resulting from poor drifting capabilities between objects. Gheisari et al. [127] pointed out the use of AR to improve healthcare facilities management but showed limited discussions regarding maintenance-related information. Similarly, studies by Ammari and Hammad [129] further supported the remote interaction elements of AR in FM. Yet, the approach they considered was criticised for being too physically demanding, requiring additional training due to its specialised skillsets as well as other critical adaptability challenges.

5.2.2. Open Standards and Semantic Web

Other efforts aimed at improving the quality and accuracy of data handling approaches were explored by many studies, including [43,130–132]. Recently, Moretti et al. [131] and Patacas et al. [43] focused on open standards with BIM and built a framework for data integration. Though it was described as flexible and easy-to-use, the framework was not validated and was restricted by its requirements for inputs based on specific data structure formats. Other researchers [133,134] have suggested that future research directions should focus on using a semantic web to support the integration of BIM with external data sources. Kim et al. [133] used the semantic web approach to improve work order processing through the integration of IFC objects and FM information. In their work, it was revealed that there is a potential to further enhance current practices by including LFF concepts as well as embedding other functions of FM. In another study, Niknam et al. [134] used a semantic web to integrate BIM with manufactured data.

5.2.3. Cloud BIM and Digital Innovations

A comprehensive description of the required standards, classifications, related vocabularies and object-oriented links for BIM in AM was discussed by Farghaly et al. [9]. However, the methodology was limited due to the absence of the required sensors and databases to retrieve relevant information. In addition, the framework could benefit from further validations with more case studies so as to enhance the understanding of its proficiency. One unique contribution was by Chew et al. [135], who applied the 5G network for smart building and smart facilities management (SFM) in Singapore and proposed a training framework that allowed higher density of internet of things (IoT) device connections, as in [136]. Other integration efforts were considered by Alwan [137], who focused on the refurbishment of housing stock, while Xing et al. [138,139] highlighted the interesting integration of Cloud-BIM enabled cyber-physical data and COBie for component reuse. However, to evolve the model platforms from prototype to practice, both strategies still need to further refine their technological solutions by enabling regulatory frameworks and feasible financial measures in the building industry.

Furthermore, Golabchi et al. [140] proposed automated approaches for FDD for HVAC systems to improve maintenance-related features. However, the proposed model is linear, which may not adequately represent real-life scenarios that are often associated with non-linearities and dynamism. Marzouk and Ahmed [141] improved maintenance scheduling and planning for water treatment plants through laser scanning. Hu et al. [142] enhanced the repair management of MEP systems through a five-step approach: managing back-ups, reporting defects, assigning repair work, updating the knowledge library and logging the repairs. However, one drawback is the manual input of data, which is time-consuming and heightens the possibilities of human errors. An interesting study by Marmo et al. [143] improved maintenance management and building performance assessment by key performance indicators (KPIs) using IFC schema. However, these KPIs were not specifically designed to reflect and/or measure maintenance performance in terms of specific maintenance activities but were rather a general/ unified set of FM tasks. The study also presents clear tracking and monitoring strategies that are designed to keep track of corrective maintenance activities, planned maintenance activities, maintenance monitoring activities, performance assessment results through KPIs and all the actors involved within these processes.

Other efforts include the application of seamless data integrations and improved collaboration as well as visualisation in smart cities frameworks [144,145], natural language processing [146], big data [67], graph theory [147], digital innovations and mixed reality techniques [72,148–152]. This review shows that there is a lack of standardised processes and procedures for seamless information exchange between BIM and O&M systems. The majority of issues lie in the interoperability between different software that require different data structures and formats. When the integration takes place, data are either lost, inconsistent or duplicated.

5.3. Maintenance Management

5.3.1. Maintenance Types and Strategies

The review revealed that 25 articles were in the maintenance management category and these are summarized in Table 3 in Appendix A. Among them, four articles focused on proposing contributions towards the improvement of maintenance management with respect to optimising the different types of existing strategies. Cheng et al. [153] developed a data-driven predictive maintenance planning framework that was based on BIM and IoT to overcome the limitations of reactive and preventive maintenance of MEP components. The framework consists of an information layer and an application layer. Although the algorithm allows better failure prediction and more efficient resource management, the algorithm is dependent on user experience and requires training and repeated testing. Piaia et al. [154] introduced a software solution to improve the maintenance inspections of historical buildings. Dias and Ergan [70] proposed approaches for eliminating system redundancy and unnecessary data by identifying missing IFC attributes and using an efficient level of details for preventive maintenance, condition monitoring and asset management of HVAC systems. This study is considered one of the few that focused closely on optimising specific information requirements for maintenance types. One of the first studies to apply advanced innovative maintenance strategies was conducted by Ma et al. [10], who proposed a data-driven decision-making approach for equipment maintenance, based on reliability-centred maintenance (RCM). However, some data requirements are unachievable in practice, such as the approximate maintenance material cost. Nevertheless, only two studies (published in 2020) addressed the term “reliability” and the concepts of reliability engineering and asset management amongst the 196 articles selected for this study. It is worth noting that, since this review focuses closely on the O&M phase, more advanced maintenance approaches are expected to emerge. This review shows that studies that clearly contribute to specific maintenance approaches are underrepresented. These benefits are either generally discussed, or rarely reported. In addition, the means and methods of reaching them remain unclear and are rarely reported in the literature.

5.3.2. Maintenance Planning, Scheduling and Visualization

Improving maintenance scheduling through optimised planning is another emerging research area within the domain of BIM–O&M integrations. Fargnoli et al. [53] showed how BIM and product service system (PSS) models can be merged to enhance the maintenance operations of building components by better scheduling maintenance interventions. Valdepeñas et al. [155] focused on improving maintenance planning and scheduling of breakwater items in port infrastructures through a comprehensive crack failure analysis. Chen et al. [156] automated maintenance work orders scheduling through simple coding to calculate the optimum maintenance time and distance. However, their work was criticized for being limited to a single maintenance team. Hence, further validation is needed to account for scenarios that involve several maintenance teams working in parallel, especially during major overhauls, outages or shutdowns (MoOSTs) [157,158]. McArthur et al. [159] proposed a machine-learning algorithm to visualise, predict and classify maintenance work orders. Lavy et al. [160] investigated the effects of using BIM and COBie data for facility management (FM) to improve the efficiency of work orders processing. Another interesting study among the few who reported the practical benefits of BIM–O&M integration was the study by Chao and Tang [161], who proposed a BIM–IFC computer system through a radio frequency identification system (RFID) to improve maintenance performance. The study findings depicted a 72% improvement in time efficiency as well as a 50% maintenance cost reduction. However, the algorithm was judged to be too complex due to its heavy programming requirements, thereby necessitating extensive training for potential users as well as the risk of compromising privacy.

5.3.3. Maintenance Budgeting

Chao and Tang [162] proposed a BIM-based integrated management workflow design for the scheduling, costs and planning of building fabric maintenance. Their study focused only on fabric maintenance, namely, curtain walls. Maltese et al. [163] on the other hand introduced a set of data, procedures and tools to allow the quantification and planning of maintenance to generate a more refined budget through the introduction of an IFC-based appraisal. The inefficient maintenance planning results from ineffective methods and techniques for predicting the uncertainties in maintenance scheduling and costs during the O&M stage. This further emphasises the importance of BIM in O&M and its potential to offer significant maintenance cost savings through better planning [163].

5.3.4. Maintenance Information Management Systems

The review also revealed three studies that focused on aspects of maintenance information management. These can be seen in the study by Ismail [51], who studied eight cases for conventional methods of precast concretes in Malaysia, where they identified key problems with existing maintenance management systems and proposed some tailored solutions. However, one shortcoming of the study is that it did not demonstrate clear benefits or justifications for how this integration can exactly adopt BIM. Another study by Moretti et al. [164] focused on smart buildings and optimised maintenance services through ultrasonic sensors and introduced a smart automated maintenance system that is triggered by pre-defined frequencies within the maintenance plan and real space usage. The limitations of this study [155] include its lack of a clear demonstration of the practical benefits in O&M, lack of clearly outlined input data to be extracted from the maintenance plans and poor accuracy levels. Wanigarathna et al. [80] proposed a framework to support healthcare maintenance engagement through more rigorous assessment of the physical condition of built assets/built asset performance data, maintenance resource data and organisational performance data. However, the framework was only validated by the built asset management (BAM) team and further involvement and perspectives of other hospital departments (especially the clinical team) are needed for the validation of the prototype. This would highlight the critical interdepartmental details of the O&M issues and would further decrease the gap between the teams, allowing for more effective maintenance planning.

5.3.5. Asset Management

Although not particularly surprising, this contents analysis further confirmed that research related to BIM and asset management integration is still in its infancy. Some of the notable studies include that by Cecconi et al. [165], which demonstrated the feasibility of transferring existing asset management procedures and tools into a BIM environment through an office building case study in Italy. The transformation helped to address qualitative asset conditions. However, further guidelines and tools are required to fully integrate BIM with computer-aided facilities management (CAFM) systems and to overcome the challenge of interoperability and the poor quality of the data. Brunet et al. [85] explored the importance of using pilot projects with feedback loops in BIM and sharing experience to support continuous improvements in AM. Munir et al. [83] focused on the business value of BIM and identified six dimensions of value that BIM contributes to AM, including management, commerce, efficiency, industry, user and technology values. Guillen et al. [166] claimed that BIM benefits within AM are not well categorised, and in turn explored how BIM can be conceived as an AM tool.

5.3.6. Other Aspects of Maintenance: Safety, Quality, Accessibility and FDD

Other essential aspects, including maintenance safety inspection, have been addressed by Wetzel and Thabet [167], who looked at delivering asset-specific safety information to FM staff prior to initiating an FM task. However, their framework was considered laborious and extremely time-consuming due to the enormous steps involved. Additionally, the FM teams were not aware of the data requirements, due to the knowledge gap between the design, O&M and FM teams. Similarly, Kim and Kim [168] studied safety inspections with BIM for bridge structures and provided an improved list of requirements for BIM-based inspections to acquire efficient statistical data. Other research efforts involving FDD can be found in [86], which supported maintenance decision making through case-based reasoning, with a focus on 21 predefined knowledge attributes. The proposed system consists of two modules: a BIM module to capture relevant information and a case-based reasoning (CBR) module to capture the operational knowledge of maintenance activities. Similarly, Motamedi et al. [169] focused on integrating BIM with a computerised maintenance management system (CMMS) to improve decision making through root cause failure analysis. However, the obvious limitations of this approach include the absence of an in-depth analysis of the assets' deterioration rates, a limited scope of failure classes covered and a lack of demonstration of how maintenance can respond to the discussed failures.

Furthermore, "design for maintenance" was first and only seen in the study by Liu and Issa [48], who focused on maintenance accessibility with BIM for an MEP component. This highlights the fact that there is a further need for more studies to focus on maintenance accessibility and maintainability with BIM in O&M. Another aspect is related to improving maintenance quality aspects in post-construction phases as in [170], in which five significant areas were identified to improve the quality and performance of FM, namely: centralised system, visualisation, simplification, modifiable system and smart emergency escape. However, no clear demonstration of maintenance-related tasks was noted in the study.

5.4. Indoor Management

Another important aspect of BIM in O&M is indoor management. This review shows that BIM applications in this domain are scarce. Only eight publications focused on indoor management, as seen in Table 4 in Appendix A. These articles addressed different contributions which are classified under thermal comfort, visual monitoring and locating buildings' components.

5.4.1. Thermal Comfort

Some studies focused on occupants and their satisfaction through enhancing thermal comfort for users. Some of the prominent studies within this domain include those by Carbonari et al. [171], who proposed a framework that combines the cyber-physical systems' (CPS) technology, the holonic approach, and overall throughput effectiveness (OTE) metrics to efficiently diagnose the causes of buildings' shortcomings in terms of indoor climate comfort, after which adequate refurbishment or maintenance plans are implemented. Similarly, Valinejadshoubi. et al. [172] focused on the virtual visualisation of buildings' thermal conditions by integrating sensor-based alert systems with BIM, which provide real time data for thermal comfort monitoring. However, the proposed approach was limited to the capabilities and quantities of the sensors deployed.

5.4.2. Visual Monitoring

Alavi et al. [59] looked at how risk assessment models can improve the visualisation of occupants' feedback and support decision diagnosis for heating, ventilation and air conditioning (HVAC) systems. Antonin et al. [173] showed how the visual monitoring of building occupancy through image recognition sensors can improve planned cost savings in FM by 40%. However, neither Alavi et al. [59], Valinejadshoubi [172] nor Antonino et al. [173] considered the clear benefits and relationships of the proposed methods on the building's O&M phase. Recently, Ergen et al. [61] formalized a strategy to integrate occupants' feedback with BIM for FM in office buildings via semantic data models. Similar efforts for real-time thermal monitoring were seen in [174,175].

5.4.3. Location of Buildings' Components

Another fundamental area in the domain of indoor management relates to the location of buildings' components as discussed by [176], who proposed a framework for integrating passive radio frequency identification (RFID) with BIM to assist indoor localisation for preventive maintenance. Yet, the study did not show precisely how the preventive maintenance activities were improved, thereby implying that the suggested framework required further validations, especially with regards to the demonstration of quantifiable benefits within the O&M stage.

5.5. Performance Assessment Management

Building performance assessments depict the ability of buildings to carry out their functions and objectives. Few research efforts have highlighted building performance assessments from various angles [177], as shown in Table 5 in Appendix A.

5.5.1. BIM Competency

Giel and Issa [14] proposed a framework to evaluate BIM competencies for facility owners. They proposed an assessment tool based on 12 specifically tailored competency categories, covering 66 critical factors used for BIM maturity assessment and highlighting that 47%, 29% and 24% were operational, strategic and administrative competencies, respectively.

5.5.2. Energy Performance

Another study for energy performance assessment discussed by [15] shows a framework for utilising feedback loops from building energy consumption to improving design and facility management, thereby narrowing the knowledge gap between the design and maintenance phases with respect to energy prediction and consumption, since it allows for a quicker design and performance review to highlight abnormal consumption trends that may require further investigation. Nevertheless, the limitations of the study include: (1) the rigour associated with structuring building management system (BMS) data prior to loading into the prototype, and (2) the data provided do not show any justifications regarding consumption levels and trends.

5.5.3. Building Deterioration

A recent study by Wu and Lepech [178] introduced a framework that integrates BIM with building durability and deterioration assessment models that are based on simulated trends. However, the assumptions of the model could benefit from further validations through multi-scenario sensitivity or parametric analyses. Following the same vein, [13] assessed residential buildings' performance through sensors and [75] focused on assessing green buildings through asset information modelling. Another area of performance assessment is information quality assessment for asset owners. Zadeh et al. [49] proposed a framework for creating and performing BIM-IQA tests for asset and space management purposes. However, the IQA dimensions are limited to the definitions of the study, thereby necessitating the need for more case examples to expand as well as validate the quality aspects.

In general, this SLR shows that the majority of performance assessment studies do not address their impacts on O&M or focus on the performance of the O&M phase itself. This implies that there is still a lack of studies addressing the critical O&M activities that are crucial to building performance. Additionally, there is a need for studies that address the questions of: what performance standards are considered acceptable for these activities and how can certain O&M performance data be operationalised to conform to a given BIM–O&M system?

5.6. Visualization Management

5.6.1. Disaster Management

Table 6 in Appendix A summarizes the studies focusing on visualisation management. Jung et al. [179] discussed fire safety and disaster management and proposed a building fire information management system that is based on management, object, information and report modules. The framework was constructed around these four modules to enhance decision making and improve the accuracy and speed of fire rescue activities. However, one of the shortcomings identified is its lack of automation, especially for fire information sensors (e.g., fire, smoke and flame). Additionally, the model can be described as still in the conceptual stage and would need to be validated by testing its robustness experimentally or using the data acquired under real-life scenarios.

5.6.2. Infrastructure Visualization

Vilventhan et al. [180] studied BIM 4D application in infrastructure relocation management, but the practical benefits of the built 4D model for underground maintenance were not explained. The bridge reliability assessment was also studied by Chan et al. [181], who proved that advanced imaging techniques can create a consistent approach to inspecting a structure and assessing for visual signs of deterioration, determining the quantities for a given maintenance work order and documenting the maintenance history. While the former research explored the visualisation of data and application navigations, Neuville et al. [47] focused on visual counting tasks. They proposed an experiment-based algorithm with the best 3D viewpoint within the BIM model for a given MEP system.

5.6.3. Failure Localization

Other integration techniques involved BIM-GIS, as in the work of Mirarichi et al. [182], which had a framework that could overcome failure localisation issues of old barcode systems that was discussed based on three premises—damage reporting, fault message forwarding and work order closing. However, the model was criticized for its user-dependence and perceived inaccuracies, which may prompt the need for further evaluations with multiple cases. Yalcinkaya and Singh [55] proposed a user interface for a visual COBie search with BIM to overcome the usability challenges commonly encountered with COBie, but did not explore the O&M phase.

5.7. Lean Management

Lean management is a new as well as interesting area of focus with regards to BIM–O&M adoption. However, only three publications were found in this domain between 2018 and 2020, as shown in Table 7 in Appendix A. Nascimento et al. [56] applied lean principles to improve FM through a conceptual framework that relates the PDCA (Plan-Do-Check-Act) cycle in the real-world application of a shale process plant. However, the study lacks an explanation of benefits adopted from the BIM-Lean approach. McArthur and Bortoluzzi [76] proposed a lean-agile FM–BIM approach to prioritize operational physical data to support asset management and maintenance activities. However, some of the challenges associated with the approach include the limited number of implemented BIM uses in the project. Shou et al. [50] have recently discussed a framework for the lean production theory to improve project management performance in turnaround maintenance projects in the oil and gas industry through a single representative case study.

6. Drivers and Barriers to BIM Adoption in O&M

Although owners perceive the promising potentials and benefits of utilising BIM in the O&M stages, many still feel uncertain about where to begin. Establishing a baseline that informs where the organisation should stand prior to the integration of BIM in O&M is one of the most critical success factors for this integration. These pre-defined drivers can support business owners in expanding their technical knowledge, refining detailed information requirements during the O&M phase and subsequently enhancing the efficiency and sustainability of the integration. This review further explores the various drivers to support and facilitate BIM–O&M integrations as summarized in Table 6. These drivers are classified into three categories, namely: technical, organisational, and legal and contractual drivers.

Table 6. Drivers to BIM–O&M integration.

Category	Description	Reference
Legal and contractual	Compliance with legislation and enforcements	[15,183]
Technical	• Optimisation of construction projects in terms of cost, time, quality and energy utilisation • Data accessibility and visibility • Improvements in maintenance planning/FDD • Renovations and feasibility studies • Optimising space management • Advanced FM via reliable tools	[8,33,45,69,87,109,135,155,181,183,184]
Organisational	• Demand from client • Achieving competence • Enhancing sustainability • Achieving a strategic value • Effective collaboration/communication platform • Management involvement	[14,45,69,87,155,184,185]

6.1. Drivers

6.1.1. Technical Drivers

One of the most important drivers for this integration is the need to digitise the predominant manual data input processes during project handover. BIM is expected to result in cost savings and a reduction in the man-hours that most FM teams will spend during the recreation of data files in their systems. This further facilitates data handling and improves the efficiency of accessing, tracking and modification through reductions in duplications and downtime [109,181]. Another motivation is the great potentials BIM can offer in terms of improving and updating preventive maintenance plans and schedules. In fact, improving the visualisation and tracking of data can enhance failure detections and reporting [183]. BIM can also be used as a tool to manage feasibility studies and propose rehabilitation models that support representative decision making to asset managers. Furthermore, within the rapid developments in technology, several methods have been proven to facilitate and ease BIM adoption in O&M through improved streamlining, such as mixed reality (MR), augmented reality (AR), artificial intelligence (AI), internet of things (IoT), virtual reality (VR), etc. [135].

6.1.2. Organisational Drivers

Once clients are aware of the potential enhancements of BIM in O&M, industry experts and facility managers then strive to reach competence and excellence in the integration process. According to Giel and Issa [14], these competencies in adopting BIM in O&M can be classified into: operational, administrative and strategic factors. Additionally, it is important to note that management involvement is vital to the success of this adoption as this pushes and motivates a collaborative platform among the different parties and stakeholders within BIM–O&M [85]. Additionally, owing to the ease of sharing and extracting data via BIM, the communication between the involved departments is improved which further accelerates this integration.

6.1.3. Legal and Contractual Drivers

The governmental guidelines and legislations push facility owners to integrate BIM in O&M to comply with legal requirements [15,183]. One of the top leading guidelines is the UK construction strategy of 2016 that mandates the use of BIM for all construction projects [25].

6.2. Barriers

In an ideal situation, BIM models should be easily linked with FM software packages and maintenance systems. However, these integrations may not always be easy or practical due to many challenges and limitations. This review classifies these barriers to BIM adoption in O&M into three categories, namely, technical, organisational and legal/contractual barriers, which are summarized in Table 7 [32,186].

6.2.1. Technical Barriers

The technical barriers include two sub-sections: method-related and data-related barriers. FM teams are not always aware of the information requirements that support BIM in O&M or the potential contributions BIM can provide [143]. This results in an unclear BIM–O&M workflow and the absence of clear guidance to enable such adoptions in the O&M environment. Another limitation is the undefined business values that BIM–O&M harmonisations can offer [8,183]. Studies show that identifying the potential return on investment (ROI) associated with BIM in this stage remains a challenge due to the absence of practical and quantifiable evidence. This hinders the integration between BIM and O&M and sometimes demotivates facility and asset owners [183]. Additionally, the design and construction phases of projects are synonymous with creating numerous files with different formats. These files become incompatible at a later phase, especially when using BIM and require modifications and re-processing which requires effort and time, and most importantly, raises the issue of interoperability [8,9,60]. This forms another issue of losing data throughout the format exchanging process. Previous studies have showed that establishing standardised libraries and BIM protocols, such as the NBS National BIM library, standardised data models, such as Construction Operations Building Information Exchange (COBie) and BIM level 2 protocols, and advanced digital programming techniques, such as customised APIs, add-ons or extensions to BIM authoring or facility management software help to minimize this gap. In addition, several studies supported the use of industry foundation classes (IFC) as a neutral data format extension which enables inter-data exchange in an information model without a loss or distortion of data [99,107,112,118,133]. However, it is important to note that these protocols do not identify the type of information that needs to be provided, when and by whom. Furthermore, BIM needs to be continuously updated, and when data are entered manually, the long process may cause inaccuracies in updating BIM models due to data duplications or unavailability [187]. Therefore, during handover, the poor quality of information (either due to the loss or absence of data) creates a knowledge gap between FM and O&M [9]. An additional drawback is the current number of software operating under the same system. FM personnel use different platforms and systems continuously, including CMMS, CAFM and Revit [67]. The selection of each system depends on various factors, such as the objectives, scope and complexity of the project. Additionally, the geographic dimensions play a major role in adapting these systems, if such integrations are to be effectively managed on a global scale. This compromises legacy systems, increases the complexity of the process, especially among stakeholders, and deaccelerates the pace of these integrations.

6.2.2. Organisational Barriers

Organisational barriers are categorised into people, culture and costs. Currently there is a lack of case studies that show real evidence of the economic benefits of integrating BIM into O&M. Therefore, clients fail to demand such integrations due to a lack of awareness of its potentials. As discussed previously, the technical challenges raise many other organisational barriers, including communication and collaboration between stakeholders and asset owners, leading to a reluctance to change, whereby teams refuse to share information with one another [16,183]. Additionally, the absence of clear guidelines for integration leads to the absence of clearly defined roles and responsibilities for both facets (i.e., BIM and O&M) [8]. Another important challenge is unclear management support and the gap between high-level business objectives and BIM models. Therefore, an effective integration between BIM and AM within the O&M life cycle phase would require inputs and support from top management to facilitate the directions for such adoptions. Aside from the initial investment costs, integrating BIM into O&M requires skills and time, thereby necessitating the provision of additional training that correspondingly heightens human resource costs [16,155,183]. Furthermore, overcoming the technical issues related to files and systems, the organisation would need to invest in information management solutions. Thus, investing a sufficient amount of funds in the pre-construction phase may be a strategic step towards successful BIM adoption.

6.2.3. Legal and Contractual Barriers

Since BIM–O&M integration requires different systems to operate, the allocation of data ownership becomes extremely complex. In addition, requirements, such as insurance and licensing, are mostly issued for limited reuse, which makes it more challenging for project stakeholders to understand the copyright restrictions associated with different classes of data [16,187]. To ensure a seamless integration, data ownership needs to be agreed on from the early stages of the project, but the authenticity and reliability of these models can be threatened by cyber security breaches. Therefore, for the cyber and electronic systems to be used for routine deployment as well as operating BIM within O&M, they must be fortified in order for such systems to appeal to organisations [173]. Table 7 depicts some of the barriers to BIM-O&M integra-tion as reported within the articles included in this SLR.

Table 7. Barriers to BIM–O&M adoption.

Category		Description	Reference
Legal and contractual		• Insurance issue • Data ownership • Privacy issues and cyber security • License	[8,16,27,32,69,71,89,173,174,187]
Technical	Methods	• Lack of standardisation, guidance and procedures • Interoperability • Undefined BIM positive business values • Lack of exchangeable and suitable formats • Volume of current operating systems	[8,9,32,33,67,68,74,77,82,85,103,104,109,135,155,167,170,180,183,184,188–190]
	Data	• Information gap between design and O&M • Undefined FM requirements/LOD • Poor quality of data • Lack of updates • Handover issues	[9,12,82,83,88,90,131,167,170,189]

Table 7. *Cont.*

Category		Description	Reference
Organisational	People	• Lack of effective communication/coordination • Lack of demands/awareness for BIM in O&M • Lack of experts/skills • Undefined roles, responsibilities • Lack of knowledge from clients FM • Lack of leadership	[8,16,33,60,82,83,85,90,101,108,183,187–189,191]
	Culture	• Centralized authority • Reluctance to change • Aligning BIM at a corporate level	[85,99,101,143,155,174,180,181,183,187,189,192]
	Cost	• Costs of training • Costs of information management	[32,69,85,155,174,180]

7. Discussion of Research Gaps

7.1. Research Gaps in BIM–O&M Integrations

This holistic review identified gaps in the body of knowledge in the area of BIM–O&M integrations. These gaps are mapped into the project life cycle of the Project Management Institute (PMI). Al Naggar and Pitt introduced a conceptual framework to manage BIM/COBie asset data using a standard project management methodology [113]. However, this study adopts the phases of a project life cycle in order to systemize the flow of knowledge gaps for all project stakeholders [193]. This can further help academics and industry professionals develop robust frameworks for BIM adoption in the O&M phase. The five phases of project life cycle as per PMI are: initiation, planning, execution, monitoring and controlling, and handover/closeout phases. Figure 11 below demonstrates how research gaps fall within these phases.

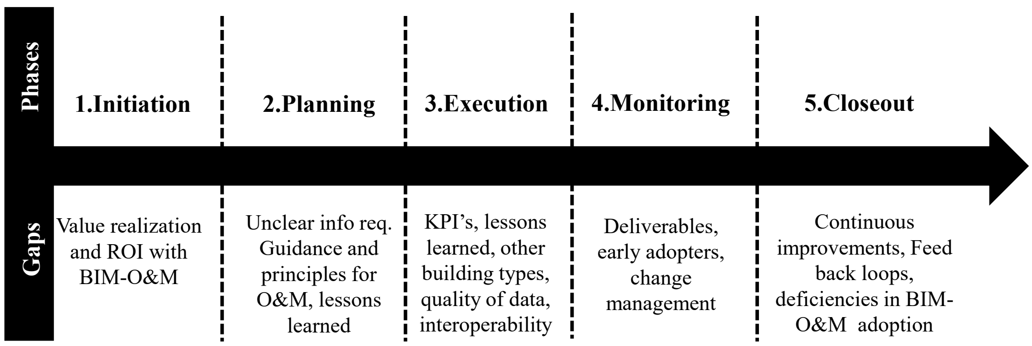

Figure 11. Research gaps mapped against the phases of the construction project life cycle.

7.2. Identification of Research Gaps

7.2.1. Value Realization and ROI with BIM in O&M at the Initiation Stage

The purpose of the initiation stage is to make sure that the scope of the BIM–O&M integration project is properly defined. This stage includes all the information required for strategic planning and investment justifications along with the value propositions for BIM in O&M. However, the ROI analysis required at the initiation stage remains a challenge. There is a gap in identifying the positive impacts of BIM in O&M. Although there are some studies reporting the general benefits of BIM in FM, very few case studies have provided proof of practical benefits in terms of cost [126,163]. The reason for this is the lack of means to quantify the benefits resulting from adopting BIM in the O&M phase of the life cycle. While the design and construction phase accounts for about 2 to 5 years of typical life cycles, the O&M phase on the other hand often accounts for approximately 20 years of the life cycle, making it more challenging to adequately assess the positive impacts of BIM. Therefore, one of the biggest challenges is to justify the ROI with BIM in O&M against the investment costs. Although few studies reported benefits in time and cost, none have clearly justified or validated how BIM in O&M can result in a positive ROI, neither theoretically nor with real case examples. Future recommendations include: studying the associated costs related to the O&M phase and the potential savings/benefits to help in realizing the positive value of BIM within the building life cycle.

7.2.2. Guidance and Principles for the Integration of BIM in the O&M Phase at the Planning Stage

After the scope of the project has been defined, the construction supply chain will plan to deliver this scope. When integrating BIM with O&M, the plan should be as detailed as possible since it is the most critical stage for setting out the foundation of the whole integration. The plan should include all the required information for specific roles and responsibilities for all stakeholders, the schedule and clear deliverables. However, facility managers and business owners do not fully understand or realize the information requirements for integrating BIM with the O&M environment [82,183]. The review shows that there are a lack of best practice and case studies addressing such integrations. Even though each organisation is different and diverse with regards to the nature of their business, there is still a research gap related to the generalisation of the requirements and information needed in the O&M scope. Further efforts are still required to explore the fundamental O&M information needs, classify these needs and identify specific deliverables, as well as the tools and methods for presenting the findings, so as to better support the integration of BIM in O&M. This review shows that the scope of O&M with BIM, the critical activities, subsystems and the required information for individual maintenance tasks within different facility types are yet to gain the desired attention. Future recommendations include answering questions such as: What type of data is required for O&M? Who should provide these data? What are the means of collecting and collating them? When should these data be integrated or collected, and how exactly should this integration fit into wider asset management strategies?

7.2.3. Interoperability and Information Logistics in the Execution Stage

In this stage, the construction supply chain and all the project stakeholders collaborate for the actual implementation of the integration of BIM in O&M. This requires data processing and transfers through the concurrent application of different software packages and programmes, which in turn raises the issue of interoperability. Interoperability remains a challenge for adopting BIM in O&M [8,9,60]. The compatibility between BIM and the different applications used during the life cycle (e.g., CMMS, CAFM and BAS) is still limited. This often entails laborious manual interventions, which are time-consuming and detrimental to the adoption process. Although a lot of studies have proposed systems architectures, frameworks and solutions to reduce this knowledge gap, the lessons learned and early adopter examples are yet to be investigated. In addition, Construction Operations Building Information Exchange (COBie) being the primary language exchange with BIM still has many limitations and is not widely adopted by the industry. Case studies prove that manual data entry in COBie and the required format structures delay the integration process [8,9,60]. This is perhaps why several studies [14,81] have advocated that some of the pressing future research areas should encompass mapping a seamless process for data exchange for BIM and O&M.

Another vital challenge in the integration is the information quality. Many software and applications are applied across the different life cycle stages of a typical building. When BIM models are integrated, the data needed from these systems lack unified structures and require individualised formats prior to data entry [187]. The literature [182] indicates that a major part of the problem is the process of updating, modifying and transferring data, which immensely contributes to the loss of information, unnecessary duplications data and quality issues. Therefore, when the integration process takes place, most data in BIM models are either inaccurate, lost or unnecessary [9]. In an attempt to alleviate this challenge, Cavka et al. [49] explored how to enhance information quality assessments with BIM for general FM requirements. However, as valuable as the findings from their study [48] are, the case examples applied were limited in complexity and dynamism, which may undermine the like-for-like transfer of knowledge gained to real-life scenarios. Therefore, future research endeavours should include identifying quality evaluation processes for a wider range of scenarios, so as to ensure information quality through the integration.

7.2.4. Performance Assessment with BIM in O&M in the Monitoring Stage

Once the integration has taken place, the project's performance is measured to ensure its compliance with schedules and budget. It is vital to identify the key metrics that actually assess the integration. To accomplish this, it is imperative to initially identify the most critical activities in the O&M phase with regards to BIM, and this is an underrepresented area within the existing body of knowledge. Many researchers have reported methodologies for assessing as well as monitoring building performance [13–15]. However, none have identified key performance indicators (KPI) for BIM in the O&M phase, although a few authors, such as Eadie et al. [16], investigated general KPIs for BIM, but were not focused on the O&M stage. Assessing maintenance performance with BIM is less explored and demonstrated and future endeavours should encompass methodologies for identifying the most critical maintenance systems for the success of BIM integration, after which they can be monitored through dedicated O&M KPIs.

7.2.5. Lessons Learned, Early Adopters and Change Management in the Closeout Stage

In this stage, the project stakeholders collaborate to perform a final quality check to ensure that the integration of BIM in O&M meets the initially stipulated requirements. Once approved, it is important to address and document all the lessons learned for continuous improvement. This review shows a lack of studies that clearly address possible inefficiencies, drawbacks and limitations that BIM–O&M integrations can encounter, which would impede the ability of asset owners to learn from previous experiences. Furthermore, managing the lessons learned from these aspects is rarely reported. Moreover, adopting BIM in O&M is expected to inform several organisational changes within the managerial and technical realms. Therefore, future emphasis should be made on incorporating learning from failure and success frameworks, so that the feedback loops address questions such as: What are the effective and ineffective O&M requirements with BIM? What are the critical O&M inefficiencies best suited to be improved by BIM–O&M integrations? What were the encountered challenges and how were they solved? What is the level of expectations of BIM–O&M and how can it be defined?

In addition, this SLR exposes the lack of case studies and expert engagements that focus on O&M for different facility types. For example, Becerik-Gerber et al. [8] conducted a comprehensive survey to identify the application areas and data requirements for BIM in FM. Their study only considered general data needs for all facility types. Nevertheless, different types of facilities have different O&M needs. Therefore, future endeavours should include conducting more focused surveys on specific building types with O&M activities at their core. This SLR also highlights that the least investigated buildings types within the existing literature are residential, industrial and commercial buildings.

8. Conclusions

Although research and practice have somewhat highlighted the potentials for BIM to support the O&M phase of a building's life cycle, studies that adequately explore how to enhance BIM-enabled facility operations and maintenance are still underrepresented. While a few review articles have attempted to harmonise the limited research outputs within this field, none of these reviews are systematic, making it difficult to ascertain the justifications for the selected articles and timeline covered. Against this backdrop, the current study contributes to the existing body of knowledge by logically evaluating, analysing and summarising the current literature surrounding BIM–O&M integrations, including identifying research trends that would eventually support the planning of future research endeavours. The well-established PRISM-P approach to systematic literature review (SLR) was used to generate, classify and justify a total of 196 retained articles. According to the scope of the study within prominent databases, such as Scopus, WoS and Engineering village, publications related to BIM integrations within the O&M phase only commenced in 2010 with a clear growing interest within the last three years. Additionally, the UK, USA and China are the top ranked countries in the discussed field. Furthermore, content analysis revealed seven thematic functions of BIM–O&M adoption, namely: information management (IM), advanced technology management (ATM), maintenance management (MAM), indoor management (InM), performance assessment management (PAM), visualisation management (VM) and lean management (LM). Most of the current research around BIM in O&M has focused on information management and advanced technologies, such as the internet of things (IoT), augmented reality (AR) and software developments. Further investigation of research trends depicts that there is a continuously growing interest in BIM–O&M studies; nevertheless, very few have actually focused on specific maintenance features and activities. A comprehensive analysis of BIM–O&M integrations focusing on specific maintenance functions is yet to be fully explored. The majority of studies focused on institutional and infrastructure facility types, but residential, industrial and commercial buildings are underrepresented, despite their disproportionate physical dominance within most societies. The study also presents an overview of the drivers and barriers hindering BIM integrations within O&M. The results of the content analyses were also mapped against the construction project life cycle, which would enable academics and industry professionals to identify and systemise research gaps and possible future directions. More studies are needed to justify the ROI for BIM within O&M, including focused surveys to identify O&M information requirements tailored to different building types as well as address the lessons learned by early adopters. Additionally, a starting point for O&M monitoring with BIM would include prioritising specific O&M data needs and defining critical indicators to measure and monitor the performance. The scope of this study was limited to the O&M phase. Therefore, other review studies should extend the scope in addressing the effects of BIM–O&M on other life cycle stages. This study can provide BIM practitioners with valuable insights regarding similar studies in the field by giving them the means and blueprints for guidance to integrate BIM within O&M. Additionally, the discussed drivers and barriers allow BIM professionals to speed up the integration process. Furthermore, the study enable decision makers to justify the specific needs to integrate BIM with O&M as well as determine the expected deliverables.

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

Appendix A

Table 1. Summary of studies on BIM–O&M in information management.

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Feature?	Building Type
[106]	A six-step systematic process for model-based facility data delivery	Needs further development of plug-in	IM	data handling	no	inst
[194]	Proposed a generic BIM-based framework for operation and maintenance of utility tunnels	Further validation	IM	-	no	FR
[54]	A BIM approach to the alignment of organisational objectives to asset requirements	The study did not focus on BIM interoperability	IM	Information requirement	no	mix
[117]	Identified five key features of maintenance management system	Poor top management involvement	IM	O&M support		mix
[111]	An efficient and effective data accessing approach with seven model function; hazard damage and health threats	Limited scope of O&M	IM	data handling	no	inst
[103]	Object-oriented data model (SIM) with high certainty and less redundancy	Interoperability with legacy systems	IM	Information requirement	no	FR
[57]	A holistic framework to align FM with BIM to satisfy owner needs	Limited scope of O&M	IM	Information requirement	no	inst
[79]	An Integrated Computerised Maintenance Management System (I-CMMS) for IBS building maintenance with efficient defect diagnosis and control	Cost and training needed for the adoption	IM	-	FDD	mix
[105]	A flexible and accurate WBS framework consisting of eight levels, such as asset management and building category	Limited scope of O&M	IM	Information requirement	no	inst
[110]	The proposed BIM-3DGIS is improved through better data management, visualisation and interoperability	Did not demonstrate quantified benefits	IM	data handling	CM	FR
[112]	BIM-based system that helps to capture and store facility information	Lacks validation	IM	data handling	no	inst
[8]	Identified information requirements and data structure via surveys regarding BIM experts and applications areas	Did not show how to link BIM to FM tasks	IM	-	no	-
[97]	Framework of seven steps to identify required data based on owners' requirement that allows clear tracking of information needs	Data is ungrouped	IM	Information requirement	no	inst

Table 1. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Feature?	Building Type
[104]	IFC and COBie do not satisfy all information requirements of asset register and service life planning by default	Country-specific, not compatible with Autodesk Revit 2014, some parameters are currently not supported with BIM	IM	Information requirement	no	-
[195]	Information were grouped by: (1) facility general information; (2) maintenance management; (3) energy management; (4) space management; and (5) asset management	Interoperability	IM	Information requirement	no	-
[12]	A customer-based organisation system to support the operational phase through seven categories and guidelines to ensure proper BIM value added activities.	Less focus on O&M; cobie was not used	IM		no	-
[101]	BIM model supporting daily FM tasks that is easily accessible, fast, clear, has live information and scheduling capabilities, addresses the benefits in the COVID-19 pandemic and does not require training to use	Lacked demonstration of actual benefits in maintenance tasks	IM	Information requirement	no	inst
[88]	The proposed framework consists of three major layers: (1) Facility information layer; (2) Maintenance information layer; (3) CMMS/CAFM information layer that guarantees comprehensive and specific data outputs, improves the data exchange process and reduces the time and effort for manual data entry	Lacks validation	IM	data handling	no	-
[123]	A dynamic BIM-based approach for H&S management during O&M with a fast way to identify possible interference between objects.	Further H&S attributes can be added and improved in terms	IM	O&M support-safety	safety for maintenance working from heights	inst
[100]	It may not be possible to develop a rigid list of requirements that are applicable to all asset owners due to the variation in business needs	Limited O&M scope	IM	Information requirement	no	inst
[74]	The theoretical framework includes: (1) the object and content of the work; (2) the information systems tools; (3) the problems; and (4) the possibility of implementing BIM in FM	Limited O&M scope	IM	-	no	inst
[89]	Improvement of components defect and knowledge transfer by analysing issues in IBS Building Maintenance in Malaysia	Country based	IM	failure analysis and FDD	FDD	mix
[58]	Novel development and application of totems through integrating BIM with FM via API Plug-in	Limited O&M scope	IM	data handling	no	inst

Table 1. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Feature?	Building Type
[102]	Focused on the critical heritage asset management activity of condition and significance-based conservation repair and maintenance (CRM) in which working practices within the heritage sector need to be carefully aligned to a BIM philosophy	Limited to heritage asset management	IM	Information requirement	no	inst
[64]	This paper provides a new EIR template and guidance document ideal for practitioners in industry	General FM; limited O&M scope	IM	Information requirement	no	inst
[107]	BIM data extraction model with a four-step process; the development of a hierarchical asset classification system; BIM model; AIM extraction platform.	IFC Schema limitations, legacy systems, resource-intensive, poor engagement	IM	data handling	no	inst
[98]	Building Handover Information Model (BHIM) framework with five information categories: location, specifications, warranty, maintenance instructions and construction specifications	Not flexible; more case studies for validation	IM	Information requirement	no	inst
[46]	The object-based framework presents detailed client requirements for project delivery to perform maintenance	Did not look into maintenance requirements	IM	Information requirement	no	inst
[125]	The system framework consists of five modules, including project documentation, personnel and contactors, FM plan and execution, technical performance evaluation, and safety and emergency management	Country based; further interpretability enhancements	IM	O&M support	daily inspection, cleanliness	FR
[44]	Identified seven core elements for BIM-FM framework	Model needs constant updating, training and quality checks	IM	-	no	-
[196]	A five-step digital 3D model with efficiency in the management of energy and economic resources with targeted maintenance interventions	Project-based	IM	-	no	inst
[197]	Suggests a master plan of power plant life cycle with three levels: "panoramic power plant, digital power plant and intelligent power plant".	Descriptive study	IM	-	no	P
[124]	An approach to create a building that is fundamentally safer by design with real-time data acquisition	Further enhancements of safety key performance indicators	IM	O&M support-safety	no	inst
[66]	Framework to characterise alignment between organisational constructs, available technology, project artefacts and owner requirements, in which numerous FM functions were examined	Formulation of computational mechanisms needed to evaluate BIM compliance	IM	Information requirement	no	inst

Table 1. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Feature?	Building Type
[90]	Improvement of data management for FM in which the framework key players are the design team, suppliers, contractors and BIM-FM team	Limited O&M scope	IM	Information requirement	no	CM
[99]	Conceptual straightforward handover data model that requires asset and geometry classifications	Requires applying previously identified mapping rules	IM	Information requirement	no	-
[118]	Schema that integrates corrective maintenance data in a three-dimensional (3D) IFC-BIM environment which minimizes lead-time, access to historical records and reduces time looking for failure causes	Limited O&M scope	IM	O&M support	corrective maintenance	inst
[108]	A textual database is created which contains the location code and item code on the asset that can quickly reach all parts and corners of the building or objects in detail as it is point cloud-based	No demonstration of the later O&M phase or any relation to FM or building life cycle with AM	IM	data handling	no	inst
[119]	The system stores all the information in digital form with three key players (inspector, manager, repairmen), resulting in high accuracy and minimal required time	Unpractical, difficulties between similar images, time and cost are unclear	IM	O&M support	no	RS
[71]	BIM implementation Matrix, a structural plan that shows the order in which the information should be implemented in a model	Limited O&M scope	IM	-	no	-
[65]	Typology matrix that shows: (1) ownership types of assets; (2) service delivery models offered; and (3) type of data and information	Lacks validation or case study to quantify potential improvements	IM	Information requirement	no	-
[52]	Three levels of information requirements: (1) maintenance personnel; (2) building management system; and (3) asset management.	Model is not very practical in terms of the number of queries and usability	IM	Information requirement	no	inst
[198]	The proposed process consists of three modules: generation of a work order, identification of causes for HVAC problems; refinement of causes. Provides a reduction in the search space and checking and tracing HVAC components	Limited information from existing FM work databases	IM	failure analysis and FDD	no	FR
[82]	The LEAD process model to improve COBie output in alignment with project-specific information requirements	Standardisation of cobie is required by policy makers	IM	data handling	No	P
[109]	BIM methodology is possible to improve maintenance, managing, or expansion of infrastructure	Limited O&M scope	IM	data handling	maintenance and repair	FR

Table 1. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Feature?	Building Type
[63]	List of product information needs for specifying project deliverables, using the example of a base-level closeout matrix	Did not explore O&M	IM	Information requirement	no	inst
[188]	The BIM execution plan proposed is based on three actions: BIM object definition, program activities and automatic data input into the database. It provides effective handling of streamed data and sustainable control, while also reducing manual work.	Limited O&M scope	IM	-	no	inst
[77]	A 10 step framework for future research on FM-enabled BIM.	Limited O&M scope & interoperability	IM	Information requirement	no	inst
[68]	A general facility maintenance knowledge database is proposed to support O&M data into the earlier phases of the project through maintainability assessment	No responses were obtained from or (MEP) staff	IM	O&M support	maintenance interventions, maintainability	mix
[84]	The developed taxonomy consists of 60 parameters categorised into six main categories: space, class, spec., warranty, asset capex and maintenance. Data input was from an asset management perspective	The proposed taxonomy focuses only on the assets consuming energy	IM	Information requirement	no	FR
[62]	The paper identified six critical activity systems that drive BIM business value for an asset owner as an evaluation of BIM maturity	Limited O&M scope	IM	Information requirement	no	inst
[78]	Studied the relationship between design modelling and maintenance software and proposed a framework for BIM in FM and identification of O&M information tools	Poor data, complexity, limited software capability	IM	O&M support	repair, fault reporting	inst
[87]	The framework has three main areas: the drivers, the barriers, and RIBA plan of work considering 35 barriers and 15 drivers for FM-DP	Unified set of FM; limited O&M scope	IM	-	no	-
[60]	Potential FM application areas that BIM can be used for the transport industry	Limited to transportation industries	IM	Information requirement	no	-
[120]	Proposed a three-dimensional location-based O&M data management system that has accurate cost management and customised O&M work planning	Needs to be validated in a real case study	IM	O&M support	no	CM
[121]	Proposed a flexible and easy three-dimensional visualized space and asset management system for large-scale airports	Did not explore relation to O&M	IM	O&M support	no	inst

Table 1. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Feature?	Building Type
[113]	A standard project management process to improve data flow among stakeholders	Interoperability	IM	data handling	no	P
[199]	Explored the potential advantages of a computerised IBS building maintenance management model	Several participants were unsure about the needed skills for the proposed model	IM		yes	Mix
[93]	Simplified BIM for O&M that consists of the critical information, including location, dimension asset information, asset capacity, specification, manufacturer, statutory, condition, and cost	Lacks further validation in real life case	IM		no	CM
[200]	Most of the FM information requirements can still be supported by COBie despite certain differences between the information required in the US and South Korea	Poor calculation assumptions for COBie	IM		no	Inst
[201]	Developed a BIM-integrated portfolio based on strategic asset management information flow framework using a non-geometric data structure	Further amending for the detailed data is needed	IM	Quality of data	no	Mix
[202]	Framework consists of an integrated maintenance database for medical equipment, scheduling and a 4D simulation module	Lacks flexibility as only one FM team assumed to do repair tasks	IM	CBR	yes	Inst
[203]	Lagging information updates of FM systems in hospital project are one of the main reasons for inefficient and costly FM workflow	Did not explore the later relation to O&M	IM		no	Inst
[94]	Key requirements are: training; increased awareness of BIM; and full support from the owner. They are divided into: top management commitment; awareness and training; and organisational technical capabilities	Results cannot be generalised. Further work is needed for validation	IM		no	
[95]	Providing qualitative in sights on how BIM-FM integration was performed in a large-scale project, and identifying the technical challenges and lessons learned	The usage pattern ofthe BIM-FM platform was not investigated in detail	IM		no	Inst
[96]	Explored the potentials of BIM technology for IBS building maintenance management	Limited awareness of BIM	IM		no	Mix

Table 2. Summary of studies on BIM–O&M in advanced technologies.

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[127]	An AR collaborative system allowing current location of users, room identification, visualizing and interaction with surroundings in real time	Accuracy issues with very high density, not practical for outdoor environment or during a power outage	AT	information accessibility	no	inst
[144]	Proposed a conceptual framework for the alignment of infrastructure assets to citizen requirements for Smart Cities	Limited data capturing, complexity	AT	-	no	-
[130]	A hybrid data mining approach on BIM-based building operation and maintenance	Limited O&M scope	AT	data handling	no	inst
[187]	A model to access building information in a health care facility through ambient intelligence	Less knowledge about the tools needed for O&M	AT		no	inst
[131]	Proposed a data-driven model to integrate OpenBIM with IoT, which is suited to dealing with incomplete data on existing buildings	As-built models are hardly accessible or even not available	AT	data handling	no	inst
[126]	A framework to support O&M fieldwork through AR with quantified actual improvements	Limited by the facility and the scenarios used for the experiment, needs validation	AT	work order processing	no	inst
[140]	This BIM plug-in guides and improves the HVAC repair operations by reducing time and efforts required by FM personnel	Deterioration model might not be linear. Faults reporting are user dependant	AT	FDD	no	inst
[150]	Automated BIM creation through the Lean-Agile FM–BIM process incorporating; space management, maintenance complaint, energy modelling	Limited complexity, quality assurance checks are required, CAD pre-processing has yet to be automated	AT	-	no	inst
[43]	A framework for asset information model consisting of owner requirements, common data environment, benefits and challenges of BIM in FM	Needs further validation, requires a specific format for structured data	AT	open standards	no	-
[137]	A framework for the maintenance and refurbishment of housing by defining the technology input method, level of data needed, and potential outputs	Limited to residential buildings, lack full implementation	AT	maintenance and refurbishment of housing stock	no	RS
[128]	Real-world application of BIM2MAR, within facility management practices with easy, cost-efficient and practical approaches	Quality issues with the drifting processes resulting in loss of data	AT	information accessibility	no	inst
[141]	BIM-FM management by clustering according to daily, weekly, monthly and annual maintenance plans	System focused (water treatment plants)	AT	maintenance information model and update plans	maintenance schedule planning	P

Table 2. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[142]	The repair management consists of five tasks: management of back-ups, report of defects, assignment of repair work, updating the knowledge library and logging the repair	Manual data input	AT	maintenance; repair information management	repair	CM
[204]	The BIMCityGML approach includes real time geometric and non-geometric (semantic) information	Limited LoD capabilities	AT	data handling	no	inst
[9]	Comprehensive description of the required standards, classifications, related vocabularies and object-oriented links for BIM in AM	Limitations due to the absence of required sensors	AT	Linked Data, asset management	no	inst
[139]	BIM and FM systems can achieve software interoperability	System focused (semiconductors fabrication plant)	AT	-	no	P
[143]	BIM-FM integration processes can be implemented and improved by an openPIM as a user-oriented asset digital twin	Limited to the healthcare facilities; KPI's does not address maintenance performance	AT	PA, M	Corrective, planned & monitoring activities	inst
[151]	Only the fine level of granularity should be used for converting BIMs to VE	Did not show actual contribution of proposed work to FM based on the case study	AT	-	no	mix
[138]	Proposed a cloud-BIM enabled cyber-physical data and service platforms for building component reuse	Short-range interrogation capability for equipment	AT	building reuse	refurbishment	inst
[192]	A BIM-based construction management system to provide virtual construction scenes	Extensive contractor involvement; compatibility with new IFC formats	AT	-	no	inst
[145]	Facility portfolio structure of the smart facility management system	Did not consider the later O&M stage	AT	-	no	-
[149]	A data-driven design approach that has a positive impact in terms of costs and results	Limited O&M scope	AT	-	no	P
[135]	A map for 5G network implementation for smart building and smart facilities management (SFM) in Singapore and with a training framework	Limited O&M scope	AT	Smart Maintenance Management & Design-For-Maintainability	real time inspection	-
[148]	Information requirements have been determined as a standard for the development of a digital model of a building, through mixed reality tools	Limited O&M scope and unified set of FM practices	AT	-	door maintenance	-
[147]	Representation of building information models for access control applications	Limited O&M scope; potential of exploring other functionalities	AT	-	no	inst

Table 2. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[134]	Integrated BIM and product manufacturer data using the semantic web technologies	Did not consider relation to O&M	AT	data handling	no	P
[133]	Proposed an object-oriented framework to integrate BIM with FM via semantic web	Can be further enhanced by learning from failures concept	AT	semantic web	no	CM
[69]	Locating building components and 3D visualisation are the most important areas BIM was seen to fit in	Limited O&M scope	AT	data handling	no	-
[67]	Developed Hadoop and BIM integration for asset management considering four sources: data sensor, mobile, RFID, open data	Less focus on O&M, costly, requires skills, lacks validation	AT	-	no	FR
[146]	A framework to match real-world facilities to BIM data using natural language processing	Did not show the relation to O&M phase	AT	-	no	inst
[129]	The integration process is based on three phases: (a) Data collection, (b) Data conversion, (c) Data interaction which	Physically demanding, requires extra training, adaptability of the system, privacy issues	AT	mixed reality; visualization	no	inst
[72]	Application of conditions data model (CDM)	Limited processing, insufficient device capacity, poor BIM content with respect to FM needs.	AT	-	no	CM
[152]	Proposed an interactive communication platform for BIM with V3DM+	Low data integrity, manual importing of data, different demands of the system function	AT	-	no	inst
[91]	The current FM practices for heritage buildings do not use advanced technology for upkeep and maintenance	Did not focus on actual maintenance practices needed for cultural heritage	AT		no	Inst
[205]	Solution for presenting and elaborating pavement condition information in an I-BIMenvironment is proposed	Inflexible, some operative issues related to the high number of road objects may occur	AT	condition assessment	no	FR
[206]	Presented a data model to integrate the building condition risk assessment model into BIM to enhance interoperability	Further analysis is needed for other functionalities.	AT	interoperability and visualization	no	Inst
[207]	High-performance algorithm to detect discrepancies between an as-planned BIM and the as-is point cloud	Inflexible model as this study did not consider the registration process for detection quality	AT		no	Inst
[208]	Realistic three-dimensional (3D) model characterised by different typologies, minimal trade-off in accuracy and low processing costs	Limitations with uploading the images	AT		no	Inst

Table 2. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[209]	DT technologies enable efficient and responsive planning and control of FM activities by providing real-time status of the building assets	Lack of a visualisation platform for different sets of parameters	AT		no	Mix
[210]	BAS-to-BIM combined strategy is introduced, and the BIM-based maintenance object framework for large-scale public venues is re-built	The model is time consuming and requires training and manual checks	AT		yes	Inst

Table 3. Summary of studies on BIM–O&M in maintenance and asset management.

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[53]	A BIM-based PSS approach for the management of maintenance operations of building equipment	Interoperability with CMMS; further analysis of PSS components	M	scheduling	scheduling of maintenance interventions	CM
[167]	Proposed a method to obtain asset-specific safety information to FM staff prior to initiating an FM task	Inefficient; owners are not aware what information is needed for FM	M	safety	no	inst
[168]	Improvements include having a BIM model and lining it with safety inspection data	Interoperability	M	safety inspection	maintenance inspection	FR
[85]	Explained the importance of using pilot projects with feedback loops and sharing experience to support continuous improvements in AM	Limited discussion on policy implications and its effect on BIM in AM	AM		no	inst
[155]	Described benefits for BIM in port maintenance	FMEA would have added great potential in terms of crack analysis or failure analysis	M	planning and scheduling	maintenance plans and schedules for O&M for breakwater	FR
[83]	Six dimensions of value that BIM contribute to AM: management, commerce, efficiency, industry, user and technology value	Limited O&M scope	AM	-	no	CM
[154]	Software solution to optimise maintenance and inspection for cultural heritage buildings	Requires replacing or updating the technical norms for condition assessment	M	maintenance planning and inspection	planning and inspection	inst
[156]	Visualisation of work order information in as-built BIM, optimised maintenance schedule by simple coding	Deals with one maintenance team; needs further verification	M	scheduling and visualization (maintenance work orders)	maintenance work orders scheduling	inst
[162]	Design of BIM-based integrated data management workflow of curtain walls	Focused only on fabric maintenance	M	maintenance (costing, scheduling)	maintenance of curtain walls	inst

Table 3. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[166]	BIM benefits for AM are not well characterised	No clear demonstration for AM in BIM, no clear discussion is made for the later O&M phase	AM	-	no	-
[80]	BAM framework input includes: physical condition of built assets/built asset performance data, maintenance resource data, organisational performance data	Limited verification, requires effort, costs and changes to management systems	M	information management system	no	inst
[86]	The proposed system consists of two modules: BIM module and case-based reasoning (CBR) module with 21 knowledge case attributes	Potential in enhancing the learning from failures concept; limited exploration of maintenance history	M	FDD	no	-
[10]	A data-driven framework to support decision making for equipment maintenance	Unavailability of data	M	RCM	RCM	inst
[153]	A data-driven predictive maintenance planning framework based on BIM and IoT with an information layer and an application layer	(1) The algorithm depends on experience of developer and repeated testing. (2) Other prediction methods were not considered in this study. (3) The predicted deterioration curves are affected by other parameters	M	predictive maintenance strategy	predictive maintenance	inst
[48]	An approach to consider maintenance accessibility using BIM tools	Limited to the fan case (MEP)	M	maintenance accessibility	accessibility	FR
[160]	It was observed that longer time was needed for processing work orders by using BIM and COBie data for FM	Lack of BIM expertise	M		work orders processing times	inst
[163]	Set of data, procedures and tools to allow the quantification and planning of maintenance budget allocation	Requires further owner's engagement in updating BIM guidelines	M	budget allocation	maintenance budget allocation	CM
[51]	Key problems in maintenance management for eight cases, categorised under four categories with proposed solutions	The study only proposed the use of BIM, but did not demonstrate clear benefits or justifications on how this integration can happen and the benefits with respect to BIM	M	maintenance information management	-	mix
[161]	Significant improvement of overall maintenance performance, 72% time efficiency, maintenance cost reduction by 50%	Computing complexity, requires training, privacy issues	M	scheduling	maintenance scheduling	inst

Table 3. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[170]	Five significant areas were identified to improve the quality and performance of facility management, namely, centralized system, visualisation, simplification, modifiable system, and smart emergency escape	No clear demonstration of maintenance related tasks	M	quality	no	inst
[169]	A framework to integrate BIM with visual analytics for failure root cause detection in FM	Reliability analysis can be further enhanced through analysing deterioration rates and studying other types of failures; did not show how maintenance respond to these failures	M	FDD; visualization	no	inst
[165]	Using BIM can result in cost savings and precision of the output	Needs to develop guidelines and procedures to store, access and share data from/to CAFM software	AM	asset condition assessment	no	CM
[159]	Investigated a series of classifier models tested to predict Work Orders (WO) subcategories	Limited O&M scope	M	visualization of maintenance WO	no	inst
[164]	A smart automated maintenance system triggered by frequencies defined in the maintenance plan	Did not show the later relation to O&M in terms of quantified improvements, lack of defined type of information required in the maintenance plans; accuracy issues.	M	smart automated maintenance system	cleaning operations	CM
[70]	Identified specific information requirement for HVAC, determined the LOD required for PM, CM, AM, and SM, which reduces redundancy in system, as major categories of IFC instances were removed	Adding missing attributes and relationships to the components and transforming component geometries to the right LODs	M	CM, PM, AM, SM	CM, PM, AM, SM	mix
[92]	Total productive maintenance (TPM) subsets can effectively prevent facility system defects during O&M	Hypothesis needs further validation in real life cases	M	TPM	yes	CM
[211]	An approach to prioritise the maintenance actions employing key performance indicators for the Building Condition Assessment-(BCA) and maintenance management.	Limited access to actual costs which might affect the estimation of life cycle costing	M	building condition assessment	yes	Inst
[212]	Proposed an assessment index system for buildings in the O&M periods in terms of the potential risk level, acceptable risk level and protection level	Only used the high degree of informatization offered by BIM and did not fully exploit its advantages.	M	fire risk assessment	no	CM

Table 3. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[213]	The automation of functions can optimise service provision, generate environmental and efficiency gains, and improve users' safety	Lack of consistent tools, methods, and devices for measuring building components performance	M	lightening	no	RS
[214]	A multi-level building system classification is developed, and fourteen specific properties are defined	Lacks flexibility to allow the implementation of the systems-centric approach	M	emergency maintenance	yes	FR

Table 4. Summary of studies on BIM–O&M in Indoor management.

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[171]	The framework measures an overall throughput effectiveness (OTE) metrics and drives refurbishment design for their enhancement	Limited O&M scope	INM	thermal comfort	no	CM
[172]	Development of an IoT- and BIM-based automated alert system for thermal comfort monitoring	Did not consider the later O&M phase; limited number of sensors	INM	thermal comfort	no	CM
[59]	BIM-based probabilistic approach to enhance occupant's comfort	No indications of the usefulness in the O&M stage	INM	thermal comfort	no	Inst
[61]	BIM can support occupants' feedback management with high satisfaction rate for users and FM personnel	Not user friendly; slow adaptation	INM	occupant feedback	no	Inst
[176]	More accurate false reporting with 64% in locating building components	Did not show relationship between improving preventive maintenance and the proposed hypothesis	INM	localization	preventive maintenance- no clear demonstration of relation	Inst
[174]	An approach to allow visualisation and real-time analysis and readings of indoor air temperature level and CO_2 concentration within the space of interest	Limited browsing features	INM	thermal comfort	no	Inst
[175]	Proposed a framework for thermal monitoring in subways	Limited O&M scope	INM	thermal comfort	no	FR
[173]	Proposed a framework for thermal monitoring in office buildings with up to 40% savings of planned costs	Not specific to O&M phase	INM	visualization	no	CM

Table 5. Summary of studies on BIM–O&M in performance assessment management.

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[15]	Framework for utilising feedback loops from building energy consumption to improve design and facility management	Specific data structures do not justify consumption levels	PA	energy performance	No	inst
[13]	Matrix of elements affecting building performance in areas, such as energy use, occupant comfort integration with technology.	Further analysis of environmental and sensor data against the energy performance data at design phase	PA	BP	No	RS
[14]	BIMCAT framework; 66 critical factors that are used for BIM maturity assessment	Needs further validation	PA	BIM competency assessment	No	-
[178]	Framework that connects BIM software with durability models of the built environment	System based	PA	building deterioration and durability	No	FR
[49]	Framework for creating and performing BIM-IQA tests for asset and space management purposes	The dimensions of IQ are limited to the definitions in the study	PA	quality	No	mix
[75]	Framework to evaluate green building performance	Limited O&M scope	PA	-	No	-
[215]	Proposed an approach for the organisation, processing, and integration of Unmanned Aerial System UAS data with BIM for automated construction progress monitoring	Did not explore the later O&M phase. Focused mainly of progress monitoring during construction	PA	progress monitoring	No	FR
[216]	Presented five key lessons to achieve whole-of-life BIM maturity and proposed a life cycle BIM maturity model (LCBMM)	Further work can involve validating the model through case studies with other conditions	PA		No	Inst
[217]	An integrated GeoBIM model of the digital built environment	The model needs further testing and development	PA		No	Inst

Table 6. Summary of studies on BIM–O&M in visualization management.

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[180]	The 4D model enhances communication and coordination between the stakeholders.	Practical benefits for maintenance are not demonstrated	V	-	No	FR
[181]	Defined a conceptual framework to improve the reliability and efficiency of bridge assessments	Further standardisation & collaboration is needed	V	inspection	inspection of cracks	FR
[179]	Building fire information management system with four modules: (1) “Management”; (2) “object”; (3) “information”; and (4) “report”	Further validation is needed, lacks automation, potential for better O&M to fire equipment	V	disaster management (fire)	Inspection	inst

Table 6. *Cont.*

Ref	Findings	Limitations	Function	Sub Function	Addressed Any O&M Features?	Building Type
[47]	Identification of the best 3D viewpoint within the BIM model	Limited to MEP systems and without extension for detailed maintenance analysis	V	-	-	-
[182]	Framework that overcomes the failure localisation issues of old barcode systems with three phases: damage reporting, fault message forwarding and work order closing.	Limited accuracy, user-dependant, needs to be evaluated on multiple cases	V	-	corrective maintenance	mix
[55]	A BIM integrated, visual search and information management platform for COBie extension	Did not explore the later O&M phase in detail	V	-	No	mix
[218]	A method for organising and retrieving photos from massive FM databases using photo metadata	Did not explore the relation to O&M	V		No	Inst
[219]	A prototype BIM-based visualisation tool Adafruit IO Reader (AIOR) was developed to interface real-time (IoT) sensor data feeds in Autodesk Revit.	Limitations in expanding the functionalities of Adafruit IO Reader	V	Fault detection	Yes	Inst
[220]	Proposed a methodology for the creation of a port infrastructure asset management tool	Further validation of the the efficiency of the developed AM tool and its usability over time in real applications	V		No	FR

Table 7. Summary of studies in BIM–O&M in lean management.

Ref	Findings	Limitations	Function	Addressed Any O&M Features?	Building Type
[56]	Conceptual framework that relates the PDCA (Plan-Do-Check-Act) cycle with BIM-Lean approaches	Lack of quantified improvements or benefits	lean management	maintenance schedule	P
[50]	Lean management framework for improving maintenance operation	Single representative case study	lean management	No	P
[76]	A six-step iterative lean agile framework is developed. The resulting BIM provided a breadth of model functionality with minimal modelling effort	Further validation	lean management	-	inst

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