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Ruwini Edirisinghe, Kerry Anne London, Pushpitha Kalutara, Guillermo Aranda-Mena,

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Building information modelling for facility management: are we there yet?

Ruwini Edirisinghe
School of Property, Construction and Project Management, RMIT University, Melbourne, Australia
Kerry Anne London
Department of Education Arts and Social Sciences, University of South Australia, Adelaide, Australia
Pushpitha Kalutara
Faculty of Science Engineering and Built Environment, Deakin University, Geelong, Australia, and
Guillermo Aranda-Mena
School of Property, Construction and Project Management, RMIT University, Melbourne, Australia

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Abstract

Purpose – Building information modelling (BIM) is increasingly being adopted during construction projects. Design and construction practices are adjusting to the new system. BIM is intended to support the entire project life-cycle: the design and construction phases, and also facility management (FM). However, BIM-enabled FM remains in its infancy and has not yet reached its full potential. The purpose of this paper is to identify major aspects of BIM in order to derive a fully BIM-enabled FM process.

Design/methodology/approach – In total, 207 papers were classified into main and subordinate research areas for quantitative analysis. These findings were then used to conceptualise a BIM-enabled FM framework grounded by innovation diffusion theory for adoption, and for determining the path of future research.

Findings – Through an extensive literature review, the paper summarises many benefits and challenges. Major aspects of BIM are identified in order to describe a BIM-enabled FM implementation process grounded by innovation diffusion theory. The major research areas of the proposed framework include: planning and guidelines; value realisation; internal leadership and knowledge; procurement; FM; specific application areas; data capture techniques; data integration; knowledge management; and legal and policy impact. Each element is detailed and is supported by literature. Finally, gaps are highlighted for investigation in future research.

Originality/value – This paper systematically classifies and evaluates the existing research, thus contributing to the achievement of the ultimate vision of BIM-enabled FM. The proposed framework informs facility managers, and the BIM-enabled FM implementation process. Further, the holistic survey identifies gaps in the body of knowledge, revealing avenues for future research.

Keywords BIM, FM, BIM adoption, BIM-enabled FM, Facility management, Whole building life cycle

Paper type Literature review

1. Introduction

Building information modelling (BIM) is widely adopted during the architectural, engineering and construction (AEC) phases, but its uptake has been slow among professionals involved in the facility management (FM) phase. Some of the early definitions of BIM in the literature (Gann *et al.*, 1996; Bjork and Penttila, 1989; Fisher *et al.*, 1997) placed little emphasis on the role of BIM in the whole-of-building life-cycle. The early definitions which did emphasise BIM for whole-of-life-cycle can be found in NBIMS (2007) and Succar *et al.* (2007), which were subsequently followed by many others. According to Succar *et al.* (2007), BIM is "a set of interacting policies, processes and technologies producing a methodology to manage the essential building design and project data in digital format

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throughout the building's life-cycle". NBIMS (2007) particularly focussed on the operation and maintenance phase, and defined BIM as "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle".

There are numerous studies that support BIM, and these have influenced the development of decision-making frameworks geared towards its adoption (Cerovsek, 2011; Eadie *et al.*, 2013; Gu and London, 2010; Porwal and Hewage, 2013; Quek, 2012; Shen *et al.*, 2010; Succar *et al.*, 2013). Many of these frameworks capture a comprehensive set of issues and make best practice recommendations. However, few studies have focussed on whole-of-life project delivery (London and Singh, 2013).

Need for BIM in FM

FM plays a key role in ensuring the effective functionality of the built environment. The International Facility Management Association (2015) defines FM as "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology".

The ability to support FM is considered to be an important value-added feature for the BIM approach (Gu and London, 2010). The American Institute of Architects (AIA Trust, 2015) defines BIM, emphasising FM, as follows: "BIM utilizes cutting-edge digital technology to establish a computable representation of all the physical and functional characteristics of a facility and its related project/life-cycle information, and is intended to be a repository of information for the facility owner/operator to use and maintain throughout the life cycle of a facility". The emphasis on FM through BIM, promises a paradigm shift in AEC and operations industry. According to Azhar (2011) this was originally limited to AEC industry.

Normally, owners and other construction project stakeholders focus on the initial design and construction costs of a building, because these occur within quite a short time period with a potentially severe impact relative to the whole life of the facility. However, the ongoing maintenance and operational costs of a building during its life-cycle far outweigh the original capital cost of construction (BIM Task Group, 2012). For a typical facility, it is believed that less than 15 per cent of the life-cycle cost is taken up by design and construction, while more than 85 per cent is taken up by FM (Teicholz, 2004). Lee *et al.* (2012) estimate that the life-cycle costs of a building could be as much as five to seven times higher than the initial investment costs. Regardless of the precise proportions, the operational and maintenance costs far outweigh the original capital cost of construction (BIM Task Group, 2012). The significant investment by clients and owners during the in-use phase presents us with an opportunity to consider the role and impact that BIM could have on FM.

As a consequence of less consideration being given to operational and maintenance actions during the design and construction phases, a massive annual loss of US$15.8 billion was recorded in 2002 in the USA alone. As indicated by the National Institute of Standards and Technology study (Gallaher *et al.*, 2004), this loss is attributable to the lack of integration and interoperability between computer-aided design, engineering and software systems.

BIM adoption in FM

Value propositions, driving forces and barriers for BIM-enabled FM have been identified in research studies (Eastman *et al.*, 2011; Becerik-Gerber *et al.* 2012; Volk *et al.*, 2014; Kassem *et al.*, 2015; Yalcinkaya and Singh, 2015; Shen *et al.*, 2016; Edirisinghe *et al.*, 2016) however, the implementation efforts are still in infancy (Shen *et al.*, 2016). Supportively, Akcamete *et al.* (2010) argued that the opportunities for leveraging BIM for facility

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operations are compelling, but that the utilisation of BIM during the building operation and maintenance phases has lagged, compared to its use during design and construction phases. A study on BIM execution trends among building owners in the USA (Mayo *et al.*, 2012) reported that more than half (56 per cent) of owners do not have BIM requirements in place to address their needs during the operation and maintenance phases. Azhar (2011) recommend that facilities managers should engage in BIM at a much earlier stage, when they can still influence the design and construction. However, one of the most critical considerations and challenges is how to give the operational needs of the owners/facility managers to maximum the influence early in the design process.

Academic debate on influence of regulations on BIM adoption is ongoing. Succar (2008) framed BIM as a combination of process, policy and technology. Supportively, BIM ecosystem (Gu and London, 2010) suggests that proliferation of, and compliance with, national standards could be one of the instruments that governments might use to promote BIM adoption, among others, such as incentives, rewards, and codes of practice. While academia continues to debate the influence of policy on BIM adoption, some countries have mandated BIM submissions, and requirements for BIM to be used in FM are also on the way. In the UK, for example, there exists a policy requiring BIM level 2 in all public sector asset procurements. The Digital Built Britain Level 3 BIM Strategic Plan (HM Government, 2015) ensures that, in future, "Level 3 will enable the interconnected digital design of different elements in a built environment and will extend BIM into the operation of assets over their lifetime […]". In Singapore, the current regulations require that architectural and engineering BIM submissions be made for all projects with a gross floor area of more than 5,000 square metres. The upcoming second BIM roadmap (Wee, 2015) is expected to promote BIM adoption to all asset stakeholders throughout the building life-cycle. As BIM for FM is becoming mandatory in some countries, a significant boost of interest in BIM-based FM can be expected in the industry.

This paper provides a systematic classification and analysis of the existing research in BIM enabled FM area. It provides a cohesive framework based on implementation lifecycle grounded by the technology adoption theory. The paper also identifies current research challenges.

2. Research methodology

Originality

Many existing literature reviews on BIM for the AEC industry place no emphasis (Gray *et al.*, 2013; Wong and Yang, 2010; Cerovsek, 2011) on projects' life-cycles. Yalcinkaya and Singh (2015) reviewed BIM studies published in the decade 2004 to 2014 by means of natural language processing of abstracts. Their broad review covered some aspects of FM, but there were very few papers on BIM in FM. The review classified core research areas, such as energy management, maintenance, and managing facilities. The focus of the paper was broad, and on BIM in general for the AEC industry, rather than specifically addressing BIM use in FM, and thus the review is limited in its usefulness for discussions of FM. Volk *et al.*'s (2014) review titled "BIM for existing buildings" focussed significantly on facility operation and maintenance, but a limited number of articles were concerned with BIM research on FM, and a majority were either on BIM or on FM. The review covered 180 publications, and only 80 of these were explicitly devoted to BIM for FM. For this reason, the main emphasis of the review was on investigating opportunities for BIM in various FM areas, rather than on real-world use of/research studies on BIM in those areas. To the best of the authors' knowledge, there has been no comprehensive review published focussing on the implementation life-cycle of BIM for FM.

In this vacuum, this paper aims to comprehensively review the research studies which have been devoted to BIM for FM through the lens of the implementation life-cycle.

Research objectives
The aims of this paper are to:

(1) conduct a critical review of the research studies on BIM for FM area through the lens of the implementation lifecycle;

(2) provide a single source of information on these research efforts through a cohesive and systematic classification;

(3) conceptualise a framework for implementation of BIM for FM; and

(4) derive recommendations for future research and for industry regarding critical gaps to be filled.

Review approach
The comprehensive review process followed three steps. First, a keyword search was performed on Google scholar and Scorpus to retrieve relevant academic articles. An additional Google search was conducted to retrieve industry publications. An iterative search process was used to reach saturation. At every search step, newly identified articles in the BIM for FM area were recorded. Any articles relating to the AEC industry without a focus on FM were excluded. The first round of search terms included "BIM and FM", "BIM and maintenance", "BIM and operations", "BIM and lifecycle", and "BIM and whole of life" and "BIM + 6D". The second round of search terms included "BIM and sustainability", "BIM and LEEDs", "BIM and retrofit", and "BIM and refurbishment". The next round's search terms included "BIM and owner", "BIM and simulation", "BIM and case study", and "BIM and pilot". There were 239 articles identified as relevant. In total, 46 articles were excluded during the second step, abstract review. The reasons for exclusion include: the abstracts being in English but the articles in a language other than English; only abstracts being available but not the full article; papers being related to learning and teaching (or pedagogy); articles being short abstracts alone, or course guides or presentations rather than peer-reviewed papers. Lastly, a few articles were not accessible (erroneous link address). In the case of a few abstracts with erroneous URLs, it was necessary to go through the university library's document delivery process to retrieve the full articles. During the content review, the third step, articles related to the same research study by the same authors (e.g. extended papers) were excluded. In all, 11 research articles were excluded. After this filtering process, 193 papers remained. An additional 14 papers were included during the review process. In total, 207 articles were included in the classification and data analysis, as discussed below.

3. Data analysis of the literature

The objective of this paper is to present a holistic view of the literature on BIM for FM with a particular focus on whole of life-cycle implementation, covering the stages from initiation through to final implementation. The content of each of the 207 research papers gathered was thematically analysed to identify its core contribution.

The first round of analysis covered English language BIM standards and guides in various countries (BCA, 2012; BSI, 2014; CRC, 2009, GSA, 2007; NATSPEC, 2011; NBIMS, 2007), and BIM for FM execution plans (Messner *et al.*, 2012). This enabled identification of the life-cycle stages of BIM implementation and their respective research areas. The articles were archived. Content analysis of other papers enabled other areas and sub-areas to emerge. The classification was recorded in a Microsoft Excel spread-sheet, and a multi-researcher approach was used to verify the trustworthiness and rigour of the thematic analysis. The themes, areas and sub-areas were agreed upon by the researchers in iterative brainstorming sessions. A subsequent iteration of classification was conducted with a

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researcher with FM expertise, which enabled the areas/sub-areas to be revised in order to verify the framework. A majority of the publications dealt with a single main research question, and thus fit into one area. However, articles that addressed more than one area were recorded in multiple areas based on their contribution. Two articles were classified into multiple areas.

The literature analysis identified ten main areas with respect to the life-cycle of BIM-enabled FM. These areas include: planning and guidelines; value realisation; internal leadership and knowledge; procurement; FM; specific application areas; data capture techniques; interoperability; collaboration and knowledge management; and other implications.

Table I shows the main areas and the sub-areas. There were a few articles on policy impacts, government roles and legal studies, and these were classified into the "other implications" area.

Please note that we use the term "BIM-enabled" as defined by Parsanezhad and Tarandi (2014): "those applications that are capable of interacting and exchanging information with BIM tools".

Figure 1 shows the distribution of research efforts in the main areas. A plurality of the papers (approximately 27 per cent) was published in the area of "pecific facility management application". The second largest category (approximately 19 per cent) fell within the

Main area	Sub areas
Strategic planning	Guides, case studies
Value realisation	Literature reviews, case studies, return on investment
Internal leadership and knowledge management	Implementation, competency, knowledge management
procurement	
Facility management	Research trends, requirements identification, case studies/pilot, frameworks
Specific application areas	Visualisation for maintenance, inspection, diagnosis, maintenance planning, safety planning, information delivery, post occupancy evaluation, energy management, retrofit
Data capture techniques	Advanced communication, 3D laser scanning, photograph analysis, case studies
Interoperability	Standards, case studies, GIS mapping, interoperability for sustainability
Collaboration and FM knowledge management	Review, collaborative practice and frameworks, case examples
Other implications	Policy impact, legal aspects

Table I.
Main and sub research areas

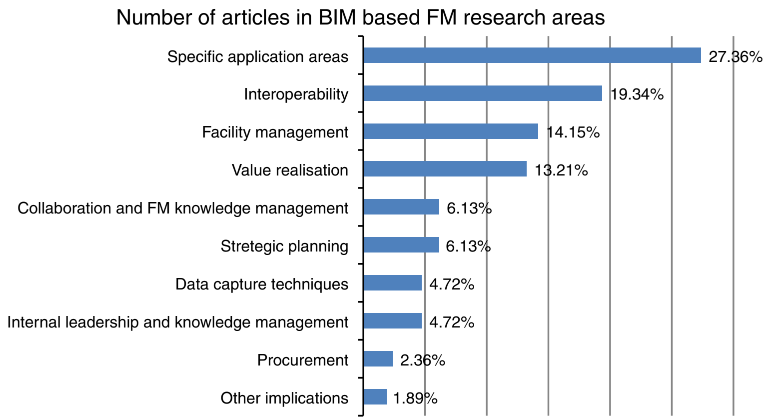

Figure 1.
Number of articles in BIM based FM research areas

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"data integration and interoperability" area. The "FM" and "value realisation" areas were of about equal research interest. The least researched areas were "procurement", and "other implications" (less than 3 per cent).

Figure 2 shows the distribution of articles in various research areas over the years. It can be observed from three publications that the significant concepts of BIM for FM emerged in the 1990s. These include: collaborative design (linking FM and occupants' needs earlier in the planning, briefing, design and construction stages for effective FM and to add value for money in FM contracts services) by Nutt (1999) and Roberts (2001); and return on investment (ROI) (ensuring value for money in FM contract services) by Akhlaghi (1996).

Active research on BIM-enabled FM appeared in the last decade, with a significant increase in publications in many areas since 2010. Interoperability issues were of almost equal interest throughout that period. Research on "specific application" areas was recorded as being great interest in the recent past. The "value realisation" and "FM" areas were also of significant interest.

Figure 3 illustrates the analysis of the articles at the sub-area level. Figure 4 illustrates further analysis of research interests at the sub-area level over time. Note that BIM-related retrofit/refurbishment has been studied widely under "specific FM application areas". Research related to the identification of FM requirements made up the second largest number of articles under the main category of "FM". "Interoperability for sustainability" (under "interoperability") and "energy management" (under "specific application areas") were equally explored, making up the third most popular area.

The next level of research interests were recorded from a literature review on value realisation, but very few papers explored the ROI. The least studied areas across all sub-areas were safety planning (under "specific application"), photograph analysis (under "data capture techniques"), and legal aspects (under "other implications"). Despite the fact that other implications, planning and guidelines, and data capture techniques were not widely studied (see Figure 2), it is interesting to note the lack of emphasis on safety planning, inspection and diagnosis application areas compared to the other specific application areas.

4. Classification and literature analysis

The research areas of the BIM-enabled FM lifecycle identified from the research papers are: value realisation, strategic planning, internal leadership and knowledge management, procurement, FM, specific application areas, data capture techniques, interoperability, collaboration and knowledge management, and other implications. The analysis enabled the classification of the articles and the identification of research gaps, as discussed below.

Value realisation

Prior to making decisions on BIM implementation, building owners should develop a strong business case to determine its value. It is vital to analyse the tangible and intangible benefits, and the organisational strategic alignment, as well as the associated costs and challenges.

Cost-benefit analysis for BIM-enabled FM has been studied in the literature using various methods. A number of studies have discussed value realisation through literature review and identification of potential benefits and challenges (Lane, 2013; Olin *et al.*, 2012; Kiviniemi, 2013; Stravoravdis, 2015; Cholakis, 2011; Abdullah *et al.*, 2014; Chew and Riley, 2013; Nutt, 1999; Talebi, 2014; Lee *et al.*, 2012; Yalcinkaya and Singh, 2015; Manning and Messner, 2008; Williams *et al.*, 2014; Williams, 2013). As discussed above, Yalcinkaya and Singh (2015) conducted a latent semantic analysis of existing literature to identify benefits and challenges. Becerik-Gerber *et al.* (2012) interviewed practitioners to identify application areas and challenges for BIM-enabled FM for existing buildings. Many studies reported opportunities, challenges and lessons learnt through the analysis of case studies or

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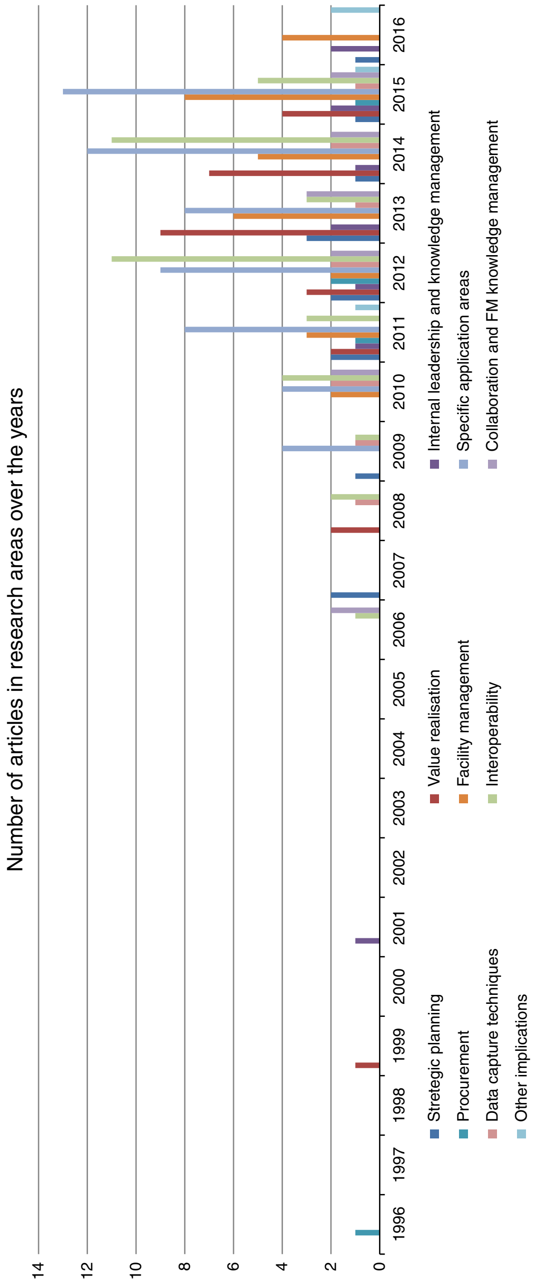

Figure 2.
Number of articles in research areas over the years

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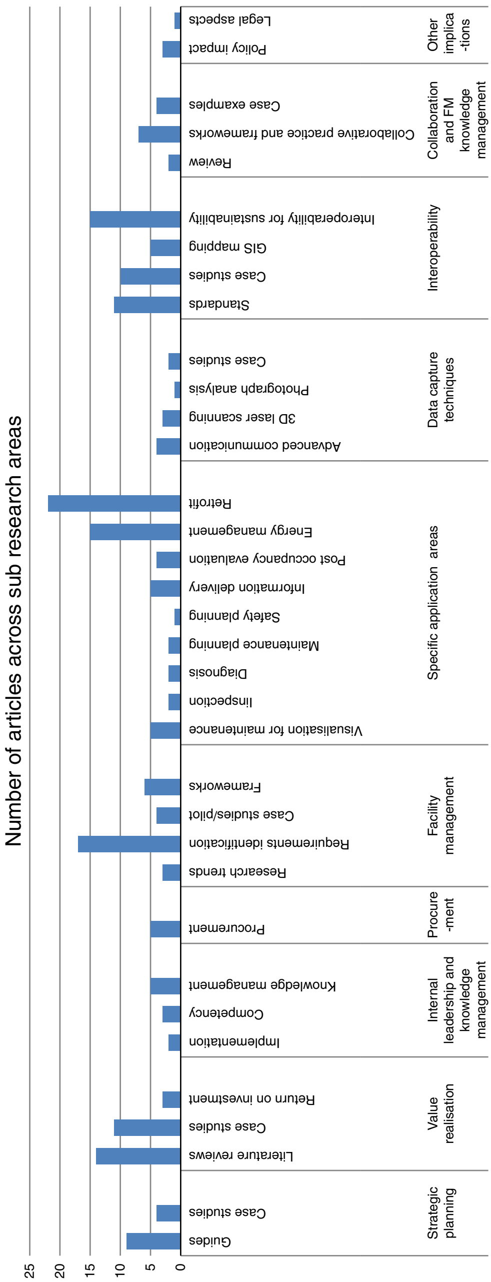

Figure 3.
Number of articles across sub research areas

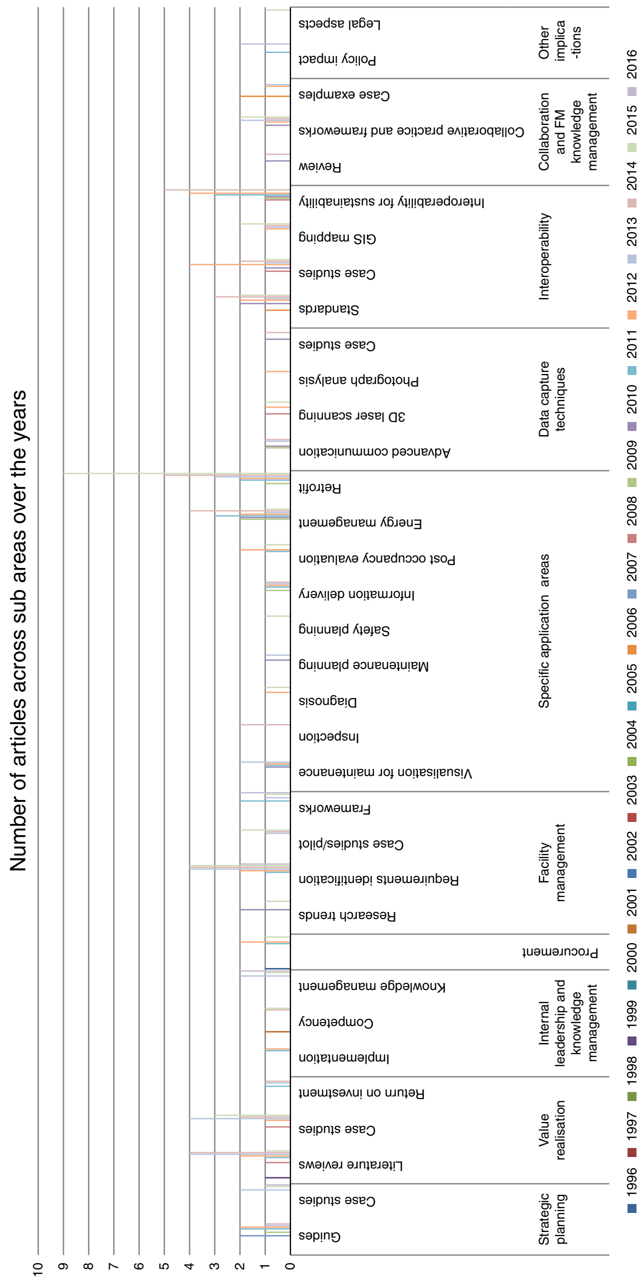

Figure 4.
Number of articles across sub areas over the years

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real-world implementations. A case study refers to an analysis done on a case study organisation or a real-world implementation of a case study building. Institutional Case studies at initial stages of BIM adoption were reported (Edirisinghe *et al.*, 2016; Shen *et al.*, 2016). Real-world implementations of BIM in university buildings (Terreno *et al.*, 2015; Kassem *et al.*, 2015; Korpela and Miettinen, 2013; Kelly *et al.*, 2013; Arayici, 2008), high rise buildings (Jupp, 2013), council buildings and a technical college (Carbonari *et al.*, 2015), a town hall complex (Codinhoto and Kiviniemi, 2014), and in an iconic structure, the Sydney Opera House (Sabol, 2008) were also reported.

FM use cases and driving forces. By interviewing practitioners, Becerik-Gerber *et al.* (2012) identified potential FM application areas as: locating building components; space management; controlling and monitoring energy, or life-cycle sustainability assessment (Volk *et al.*, 2014); planning and feasibility studies for non-capital construction; and emergency management. Mechanical, Electrical and Piping system management and condition assessment (Eastman *et al.*, 2011) is also a potential application area. Kassem *et al.* (2015) tested the value of BIM-enabled FM using a case study and found that accurate defect detection (Volk *et al.*, 2014) and fault reporting is achievable through the integration of the model (Kassem *et al.*, 2015). In the retrofit and refurbishment areas, rapid evaluation of retrofit or maintenance impacts (Eastman *et al.*, 2011; Becerik-Gerber *et al.*, 2012), scenario planning (Kassem *et al.*, 2015), monitoring scenario based performance measurements, and risk scenario and execution planning (Volk *et al.*, 2014) were identified as significant use cases. Visualisation can assist FM personnel in various ways, including localisation of building components, and indoor navigation (Volk *et al.*, 2014) including potential for room finding (Kassem *et al.*, 2015) through bespoke plans, elevations and visual renders from the same single digital model source.

Value propositions for BIM-enabled FM have been identified in building operations from commissioning to maintenance; more efficient building commissioning (Eastman *et al.* 2011) and information handover for FM (Kassem *et al.*, 2015) are among them. Data handover enables rapid population of FM databases (Eastman *et al.* (2011) with accurate FM data (Kassem *et al.*, 2015). This automated data population (Becerik-Gerber *et al.*, 2012) is more efficient than manual data entry (Kassem *et al.*, 2015). This can be achieved through information transfer, beginning at the earliest stages of the building process (Yalcinkaya and Singh, 2015). Benefits can be achieved by applying BIM as a tool (Eastman *et al.*, 2011) in a number of maintenance areas, as discussed above, through simulated facility operation (Eastman *et al.*, 2011). Practitioners perceived benefits of BIM to be: facilitating real-time data access, visualisation and marketing, creating and updating digital assets, and personnel training and development (Becerik-Gerber *et al.*, 2012). The ability to attach compliance data (Kassem *et al.*, 2015) is also noted as a benefit. In another study by Yalcinkaya and Singh (2015), key word analysis captured additional benefits: increased efficiency of work orders and of decision-making processes.

A recent study (Shen *et al.*, 2016; Edirisinghe *et al.*, 2016) revealed internal organisational and external motivators through in-depth interviews with FM practitioners in two international institutions. In addition to the operational efficiency, performance and cost benefits identified in the literature, a desire to be ahead (to be voluntarily innovative), and other stakeholders' adoption of BIM in their workflows (Shen *et al.*, 2016) were found to be internal motivators. The ability to use BIM models for preventive maintenance, as a single source of information in contrast to the significant number of software systems currently in common use, were also found to be motivators (Edirisinghe *et al.*, 2016). Among the external motivators for FM professionals to adopt BIM in FM are encouragement and enforcement by the authorities, organisational image, the peer effect (Shen *et al.*, 2016), industry push, and potential competitive advantage (Edirisinghe *et al.*, 2016).

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Challenges. Eastman *et al.* (2011) classified the barriers to implementing BIM-enabled FM as either process or technology barriers. Among the process barriers are market readiness (too early), right project phase (too late), and massive training costs and lengthy learning curves (Eastman *et al.*, 2011), which Kassem *et al.* (2015) also identified as a barrier through case study analysis. Lack of collaboration – which Yalcinkaya and Singh (2015) also identified through keyword analysis – legal barriers, and issues of model ownership and management are the other process barriers. As Eastman *et al.* (2011) argue, a lack of technological readiness for integrated design and standardisation are technology barriers); Yalcinkaya and Singh (2015) agree. Supportively, interviews with practitioners revealed that the lack of technology readiness as an organisational barrier (Shen *et al.*, 2016). Relating to standardisation, interoperability between BIM and various FM technologies (Yalcinkaya and Singh, 2015; Kassem *et al.*, 2015) is a significant challenge. Recent studies (Yalcinkaya and Singh, 2015; Kassem *et al.*, 2015; Edirisinghe *et al.*, 2016) have identified that the lack of clear requirements for the implementation of BIM in FM in the early stages of projects is another barrier. Succar *et al.* (2016) propose using model-based deliverables to clarify these requirements. In addition, Kassem *et al.* (2015) argue that the lack of methodologies that demonstrate the tangible benefits of BIM in FM (Shen *et al.*, 2016), and an absence of real-world case studies, are challenges. Kassem *et al.* (2015) also highlighted the need for users to accept the technology in order for it to become more widespread. A rigid industry culture with regard to the adoption of new processes and technologies is also perceived to be a barrier (Kassem *et al.*, 2015). Additional challenges were identified concerning ROI analysis as a result of the significant intangible benefits and long period of time taken before the value of BIM is realised (Shen *et al.*, 2016). Interviews of institutional practitioners revealed the challenges around setting of organisational priorities for BIM, especially when the core business of the organisation in question is not asset management (Shen *et al.*, 2016; Edirisinghe *et al.*, 2016).

Volk *et al.* (2014) argue that most research deals with enabling BIM in new buildings, while studies intended to address issues relating to BIM for existing buildings are very few. Existing buildings present additional challenges, with the need to digitise plans and for the use of technologies such as 3D laser scanning (Arayici, 2008) to develop a digital model. Interviews with practitioners have revealed (Becerik-Gerber *et al.*, 2012) additional challenges for BIM-enabled FM for existing buildings, such as defining data requirements, roles and responsibilities for loading data into the model, maintaining the model, and lack of real-world cases and proof of positive ROI.

Love *et al.* (2013, 2014) propose a benefit evaluation framework that looks beyond ROI and takes into account the evolving nature of BIM by incorporating intangible benefits. As Eastman *et al.* (2011) argue, owners may be unaware of the benefits that can be derived from a BIM process, and thus it is vital to justify the investment in BIM, considering both ROI and intangible benefits.

Strategic planning

Once the decision is made to implement BIM, the next phase is to develop a plan and guidelines. BIM planning (Messner *et al.*, 2012) and guideline development (Eastman *et al.*, 2011) is a critical phase for successful BIM implementation in an organisation. Various national standards and guidelines have been developed for BIM implementation, some of which specify the use of BIM for FM. These include the standards and guidelines in the USA (NBIMS, 2007; GSA, 2007), the UK (BSI, 2014), Australia (NATSPEC, 2011; CRC, 2009), and Singapore (BCA, 2012). Teicholz (2013) developed guidelines specifically for facility managers. Eastman *et al.* (2011) recommend identifying BIM goals that are aligned with the organisational goals, to define the scope and use of BIM across phases of projects, to define the scope of standards or formats for information exchange, and the roles of participants in the BIM process and between handovers. Messner *et al.* (2012) recommend developing a strategic plan for BIM. The strategic planning procedure ensures an assessment of the organisation's current levels of internal and external BIM integration, alignment with current organisational BIM goals, and the definition of an advancement strategy.

The BIM planning procedures were verified through the analysis of a case study of an institutional building project by Chunduri *et al.* (2013). Although it did not focus on BIM implementation for FM, the study dealt with the owner organisation of a well-established real estate development firm to illustrate the process of using the BIM organisational strategic plan and BIM project procurement plan. The study recommends proper planning, time and resource allocation based on an implementation roadmap to increase the likelihood of success. Implementation processes were also reported in case studies of a building project in Taiwan (Lin *et al.*, 2016) and of university buildings (Kensek, 2015; Gleason, 2013).

Internal leadership and knowledge

Messner *et al.* (2012) recommend developing a BIM implementation plan after developing the strategic plan. This includes a process that maps BIM integration, information requirements, technology infrastructure requirements, and education and training requirements. Eastman *et al.* (2011) call this phase "internal leadership and knowledge building". The steps in this phase include developing internal knowledge about BIM technologies, and assigning owner-dedicated personnel to lead the effort. However, there is no evidence presented in their work that any of the phases related to internal leadership and knowledge of these two guides (Eastman *et al.*, 2011; Messner *et al.*, 2012) were tested and validated on real projects. In support of implementing the above planning guides, Giel and Issa (2015) provide a framework for evaluating the BIM competencies of facility owners. Their framework is composed of 12 different competencies in the following categories: operational, strategic, and administrative. Corporate competence in FM was also studied by Roberts (2001).

Knowledge management and early involvement of FM were studied in a number of articles (Lindkvist, 2015; Russell *et al.*, 2013; Kivits and Furneaux, 2013; Bonanomi, 2016a, b). Lindkvist (2015) studied the knowledge management aspects of BIM-enabled FM to highlight the need for early involvement of facility managers in projects. The study aims to address the lack of understanding of learning processes for BIM in maintenance during the design/early building stage. Both exploitive and explorative learning mechanisms are considered in his study. A new building project which had adopted BIM was selected as the case study, and the researcher interviewed its project and maintenance managers. The findings reveal that the "early involvement of maintenance professionals in the design stage" introduces effective workflows for better collaboration and information flow. The study also introduces a knowledge management practice and learning curves for maintenance and design professionals, which can optimise the changing of processes involved with BIM adoption.

Procurement

Akhlaghi (1996) highlighted the need to ensure value for money in FM contract services. Eastman *et al.* (2011) refer to this phase as "service provider selection", which includes knowledge management (to ensure that the service providers are conversant with BIM), including BIM-specific criteria, and evaluation of the BIM capability of service providers. Messner *et al.* (2012) recommend having a procurement plan for all new construction or renovation. The components of the procurement plan include team selection criteria to enable the procurement of qualified items, contract requirements to define the BIM

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deliverables, and a standard BIM project execution plan template to initiate the detailed BIM planning process for the project. Mayo *et al.* (2012) studied the contract specifications and BIM requirements among building owners.

BIM-enabled FM

Regardless of whether the building is new or an existing one, the ultimate objective of a BIM model is to use it in FM, which has the potential to significantly reduce life-cycle cost. A number of aspects related to BIM-enabled FM were studied, including:

- reviews (Becerik-Gerber and Kensek, 2010; Shen *et al.*, 2010);
- FM requirements identification (Volk *et al.*, 2014; Becerik-Gerber *et al.*, 2012; Almarshad, 2012; Liu and Issa, 2015; Abdullah *et al.*, 2013; Patacas and Kassem, 2015; Reddy, 2011; Al-Shalabi and Turkan, 2015; Mayouf *et al.*, 2014; Simeone *et al.*, 2013; Liu and Issa, 2013; Parsanezhad, and Dimyadi, 2013; Ahn and Cha, 2014; Liu and Issa, 2014);
- functional case studies (Cavka *et al.*, 2015; McArthur, 2015; Lindkvist and Whyte, 2013; Orr *et al.*, 2014); and
- frameworks (Lin and Su, 2013; Su *et al.*, 2011; Hallberg and Tarandi, 2011).

Among the studies that captured maintenance requirements, some paid specific attention to existing buildings (Volk *et al.*, 2014). In order to identify FM requirements, these studies use personal and expert interviews (Becerik-Gerber *et al.*, 2012) and/or surveys (Liu and Issa, 2015). While some studies were devoted (Patacas and Kassem, 2015) specifically to analysing the requirements on maintained information, others (Mayouf *et al.*, 2014) analysed the requirements from the perspectives of the building delivery team, the facilities management team, and the building occupants.

Functional case studies were presented on university buildings (Cavka *et al.*, 2015; McArthur, 2015; Orr *et al.*, 2014), and buildings and parks for an Olympic Games (Lindkvist and Whyte, 2013). Cavka *et al.* (2015) analyse the process-oriented configuration of design and construction BIMs to satisfy the owner's operational and maintenance needs, including the owner's technical guidelines, software and systems, and associated information flows. A building owned by an institutional organisation served as the case study. The researchers conducted an analysis of handover artefacts, and conducted interviews and a walk-through of the BIM model with maintenance personnel. The aim was to understand the information requirements, available tools and processes, areas of improvement, and areas that would benefit from BIM implementation. The study identified that problematic commissioning practice (not having the input of operational personnel during design and construction) led to issues in the operations phase. In addition, there were issues related to compliance in terms of handover artefacts, and with the building equipment design criteria, such as installation requirements, equipment accessibility, and clearance requirements for accessibility. The walk-through of the design model identified missing geometry, missing information related to components and systems, level of detail issues, and modelling problems. The prototype tested by Orr *et al.* (2014), demonstrates the feasibility of the system as an aid to decision-making processes of FM for daily activities. This was showcased by wall repainting activities that led to cost savings as a result of using the right decision-making method under the model.

Among the frameworks are: a mobile-based maintenance management system verified through a case study (Lin and Su, 2013), a school maintenance system with schedule management, condition coding, document management, progress monitoring and inspections (Su *et al.*, 2011), and a life-cycle management system (Hallberg and Tarandi, 2011)

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that supports inventory, condition surveys, service life performance analysis, maintenance planning, maintenance optimisation, and maintenance analysis – case study of Norrtälje Hospital, owned by a County Council and by private healthcare actors. The study by Lin and Su (2013) proposed using mobile devices for maintenance and operation works on site. In their study, facility maintenance management (FMM) was linked with BIM technology to track and control the FMM process via tablets with web-cams. A pilot case study of a commercial building in Taiwan and its critical facilities was used to verify the proposed methodology. Lack of familiarity with the system, especially with the BIM models, the constant updates needed on the BIM model, and the long download times of the integrated BIM models were reported as challenges to implementation of the technology.

Specific FM application areas

Interviews with practitioners revealed that locating components, facilitating real-time data access, checking maintainability, and automatically creating digital assets are among the top priority application areas (Becerik-Gerber *et al.*, 2012) in implementing BIM-enabled FM. Other application areas include visualisation and marketing, space management, planning and feasibility studies for noncapital construction, emergency management, controlling and monitoring energy, and personnel training and development. Recently, based on a literature review, Volk *et al.* (2014) presented the issues related to these applications as "functional issues". They classify BIM for FM application areas as: energy/thermal analysis and control, carbon foot-printing; localisation of building components, indoor navigation; life cycle assessment, sustainability; monitoring, performance measurement (through sensors); retrofit/refurbishment/renovation planning and execution, and space management.

BIM implementations were reported for some of the functional areas identified above. BIM was used for visualisation in facility maintenance (Koch *et al.*, 2012; König *et al.*, 2011; Costin *et al.*, 2013; Krukowski and Arsenijevic, 2010; Santo *et al.*, 2013). Koch *et al.* (2012) used augmented reality markers for navigation. Santo *et al.* (2013) included building users as active participants to capture operating requirements. Costin *et al.* (2013) and Krukowski and Arsenijevic (2010) used BIM for the purpose of maintained-related navigation.

Lin *et al.* (2014) used BIM for inspection purposes to record the information in barcodes, while Ammari and Hammad (2014) used real-time video and sensor data for inspections. Zimmermann *et al.* (2012) and Yang and Ergan (2015) used BIM for fault detection and diagnosis during maintenance activities. Akcamete *et al.* (2010) utilised the building model for planning maintenance activates. whereas Drogemuller (2013) proposed using BIM for emergency management (to model emergency scenarios). Wetzel and Thabet (2015) proposed using BIM to support safe facility operation processes.

BIM has been used for information delivery purposes in health care facilities (Lucas *et al.*, 2012; Lucas, 2012; Wang *et al.*, 2015; Lucas *et al.*, 2013). Motamedi *et al.* (2014) developed a prototype of a knowledge-assisted BIM-based failure root-cause detection system integrated with a computerised maintenance management system (CMMS). A case study of an institutional building was selected to virtually analyse the root causes of temperature problems in a room based on fault trees. This concept of visual analytics was also used to link with RFID for localisation (Motamedi, 2013). It has also been proposed, for operational information management purposes, that BIM be linked with RFID (Hammad, 2009; Cheng and Chang, 2011) for life-cycle information delivery.

Post-occupancy evaluation has been studied as a functional area (Ozturk *et al.*, 2012; Mcginley and Fong, 2015; Coates *et al.*, 2012; Li, 2011). Li (2011), for example, used the criterion of thermal comfort.

A number of studies have dealt with BIM for sustainability or energy management. Frameworks for BIM-enabled energy management (Zhang *et al.*, 2014; Park *et al.*, 2012; Azhar and Brown, 2009; Wong and Fan, 2013) have been conducted on energy and costing

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(Nour *et al.*, 2012), energy efficient test-beds (Redmond *et al.*, 2010), and incorporating knowledge systems (Motawa *et al.*, 2014). Among the energy-related instances are (Wang *et al.*, 2011; Raftery *et al.*, 2011; Azhar *et al.*, 2009; Wong and Kuan, 2014), where the real implementations were from facilities (Azhar *et al.*, 2010), residential houses (Raheem *et al.*, 2011), and medical facilities (Eguaras-Martínez, 2014).

BIM was used in a significant proportion of studies on FM for retrofit or refurbishment projects. This area was reviewed by Bu *et al.* (2015), Ilter and Ergen (2015), and Gholami *et al.* (2013). Energy and sustainability was widely studied in this space (Elmani, 2015; Hammond *et al.*, 2014; Larsen *et al.*, 2011; Russell-Smith and Lepech, 2011; Woo and Menassa, 2014; Yang *et al.*, 2013; Ghosh, 2015, Vital and Cory, 2015; Chaves *et al.*, 2015; Comlay and Tzortzopoulos, 2015; Wang *et al.*, 2015; Fouchal *et al.*, 2015; Liu *et al.*, 2014b; de Freitas and Ruschel, 2014; Woo and Gleason, 2014; Tuholski and Tommelein, 2009; Wu, 2013; Sheth *et al.*, 2010; Boeykens *et al.*, 2012). Jiang *et al.* (2012) studied server requirements to support energy-efficient retrofit.

Data capture techniques

Among the various technologies proposed for FM data capture and information retrieval are advanced communication technologies, such as sensor technologies (Hajian and Becerik-Gerber, 2009; Vähä *et al.*, 2013), RFID tags (Meadati *et al.*, 2010), 3D laser scanning (Yoon *et al.*, 2015; Arayici, 2008; Bosché, 2012), and photograph analysis (Bhatla *et al.*, 2012). Case studies were conducted in a University (Onyenobi *et al.*, 2010), and in the oil and gas industry (Shou *et al.*, 2014) to test some data capture techniques.

Interoperability and data integration

Defining the FM data. Defining the right hierarchy of elements is a fundamental challenge in FM in general. Edirisinghe, Setunge, Zhang and Wakefield (2012) argue that the identification of the element hierarchy of a particular infrastructure system for FM requires a trade-off between the level of detail/depth of elements vs the cost of data collection and other practical limitations, where cost can be seen in terms of money, as well as time and data accuracy. In decision-making related to building management (BM) for complex infrastructure assets, such as buildings, it is vital to conduct a component-level analysis rather than an analysis of the entire building stock (Edirisinghe *et al.*, 2015). The ideal structure captures the rich set of data related to FM, including condition monitoring data, which can be collected visually or through automated processes. Studies have discussed the data requirements for BIM-enabled FM, and have proposed and considered both geometric (Volk *et al.*, 2014) and non-geometric data structures (Becerik-Gerber *et al.*, 2012; Volk *et al.*, 2014) for BIM modelling.

System and data integration. A large number of proprietary FM information and software systems are currently in use, including CMMSs, computer-aided facility management systems (CAFMs), integrated workplace management systems (IWMSs), electronic document management systems and energy management systems (EMSs), building control systems, and enterprise resource planning (ERP) systems. One of the major challenges in achieving BIM-enabled FM is bridging the gap between the BIM system and the FM system already in place; this is because information transferred from design and construction is not integrated or compatible with existing FM information systems, and thus they do not support FM practices. Shen *et al.* (2012) developed a conceptual framework of the proposed agent-based service-oriented integration approach for the integration of facility life-cycle information. The platform is designed to accommodate various integration requirements for condition-based maintenance, real-time data collection, wireless sensor networks, and BIM applications. It allows integration of existing hardware and software

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systems from different vendors, with different communication protocols, in different versions, including almost any legacy system (according to the authors). A local research facility was studied to verify the concept of integrating the BIM system, the heating, ventilating, and air conditioning (HVAC) control system, the local weather station, the building façade monitoring system, the equipment and people tracking system, the equipment condition monitoring system, and the fire response and evacuation simulation system.

BIM and interoperability. It is vital to bridge the gap between data requirements in FM and BIM for seamless system integration, using IFC as the vehicle (Mitchell and Hans Schevers, 2006). The need for interoperability is growing (Jardim-Goncalves and Grilo, 2010; Parsanezhad and Tarandi, 2014). The Construction Operations Building Information Exchange (COBie) specification (East and Nisbet, 2010) provides a Microsoft Excel Spread sheet-based structure for FM data. Whilst there is a clear need to integrate FM systems with BIM models, it is doubtful whether a specification such as COBie (Open BIM Network, 2016), as used in some cases (Lavy and Jawadekar, 2014; Lavy and Saxena, 2015), is the right solution (Yalcinkaya and Singh, 2015; Kassem *et al.*, 2015), due to the lack of clarity on information use (East and Carrasquillo-Mangual, 2013a, b). Included among the research efforts on the subject of interoperability are evaluations of IFC and COBie (Patacas *et al.*, 2014; Patacas *et al.*, 2015), and of linking BIM with building performance data (Cahill *et al.*, 2012), as well as investigations of CAFM requirements (Gnanarednam and Jayasena, 2013; Clayton *et al.*, 2009).

Other case studies related to interoperability issues (Jawadekar, 2012; Drogemuller *et al.*, 2008; Kasprzak *et al.*, 2013) include HVAC management (Rosen, 2010; Yang and Ergan, 2014), energy performance (Somboonwit and Sahachaisaeree, 2012), GIS mapping with BIM (Kang and Hong, 2015; Taneja *et al.*, 2012; Wu *et al.*, 2014; Kim *et al.*, 2015). Interoperability of BIM for sustainability was also widely studied (Carbonari and Jones, 2014, Nguyen *et al.*, 2010; O'Donnell, 2014). There were also studies involving the LEED IFC model (O'Keeffe, 2012; Barnes and Castro-Lacouture, 2009; Wu and Issa, 2014; Crosbie *et al.*, 2011), the BEAM model (Wong and Kuan, 2014), an energy model linked with ontology (Muthumanickam *et al.*, 2014), server requirements (Jiang *et al.*, 2012), and Building Automation Systems with the energy-enhanced BIM (Forns-Samso *et al.*, 2012).

Collaborative practice and FM knowledge management

The ultimate objective of developing a BIM-enabled model for FM is that facility managers will adopt the technology for better facility maintenance and operations. Hence, it is vital to have users involved in the technology development process. Prior to starting the development process, it is vital to capture users' needs so that the system can meet their expectations; as is done in software engineering, in which user requirement analysis is a major phase in the development cycle. Similar user consultation is critical in BIM-enabled FM prior to system development, if the technology is to make an impact. Integration and collaboration that emphasises FM (Shen *et al.*, 2010) and knowledge-based BIM (Charlesraj, 2014) have been reviewed by researchers. Collaborative practice and knowledge management are connected, making the life-cycle into a feedback loop. Studies in this area include Xu *et al.* (2014), Hungu (2013), Liu (2012), Jordani (2010), Motawa *et al.* (2015), and Motawa and Almarshad (2013), and there have also been a number of relevant case studies (Wang *et al.*, 2013; Ballesty, 2006; Kasprzak *et al.*, 2013).

Jordani (2010) identified the downstream use of BIM in FM during the design and construction phase. A number of owners and facility managers were surveyed to determine their expectations for the use of BIM on their projects. The survey revealed a trend among owners towards using BIM data to support operation and maintenance. Slow adoption rates of BIM among owners were believed to be due to their initial lack of understanding and the

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dearth of documented metrics on the costs and benefits of BIM. The study identified almost no examples of BIM data being fully utilised for FM, although the information captured in design/ construction BIMs can be leveraged for downstream use for FM. Jordani argues that a pre-requisite for effective integration of BIM and FM is that the data captured in BIMs must be channelled into a variety of FM software, such as CMMS, CAFM, IWMS, building control systems, and ERP systems. Jordani suggested a solution called a BIM portal, based on a system architecture in which a virtual model of the facility serves as the front end – a one-stop shop for the owners' disparate FM software.

Wang *et al.* (2013) developed a framework to apply FM in the design phase, using BIM to improve collaboration and knowledge management practices involving information sharing and gathering. They designed a BIM database based on a literature review and common FM practices in a real-world project. FM was identified during the design phase as including maintenance and repair, energy management and commissioning. The framework has the potential to reduce issues such as reworking and inappropriate allocation of workspace in the operational phase.

Motawa *et al.* (2015) developed an integrated system to capture, retrieve and manage information/knowledge for one of the key operations of BM. The concept of building knowledge modelling has been applied utilising KM techniques in BIM. A case-based reasoning module (CBR) was developed to capture knowledge gained in BM operations. A computer system was developed with CBR for BIM. The knowledge case attributes were designed based on various project documents. The analytical hierarchical process technique was utilised to rank and weigh first and second level attributes through focus group interviews. This system has the potential to help professionals make informed decisions supported by previous experiences based on a comprehensive database. The database has the potential to store the full history of building operations, which is valuable to building owners and facility managers in an easy searchable format to be used for future purposes.

Other implications

Among the under-studied areas of BIM adoption in FM are the impact of policy (Wong *et al.*, 2011), and legal aspects (Olatunji and Akanmu). Some countries have already mandated BIM submission in the design phase, and have upcoming policies for its use in the FM phase, such as the Digital Built Britain Level 3 BIM Strategic Plan in the UK (HM Government, 2015), and the second BIM Roadmap in Singapore (Wee, 2015). While there is no federal policy mandating the use of BIM in Australia, some state-level initiatives have recently appeared. For example, New South Wales Health Infrastructure has mandated BIM deliverables on all projects valued over $30 m since 2013 (NSW Government, 2016).

5. Discussion

The BIM implementation life-cycle research areas identified through the classification of the articles was mapped against the highly cited and well accepted technology diffusion theory (Rogers, 1995) to derive the BIM enabled FM framework as shown in Figure 5. The analysis has identified the distribution of overall research interests across the research areas and sub-areas, as well as research interests across the years. The holistic review identified gaps in the body of knowledge which are illustrated in the framework and are also discussed below.

Technology diffusion theory and BIM for FM life-cycle

In the case of FM, the building owner/client organisation is the unit of adoption rather than the individual, so research on diffusion of innovations in organisations is more relevant. Organisations are created to handle large-scale routine tasks through a pattern of regularised human relationships (Rogers, 1995, p. 375).

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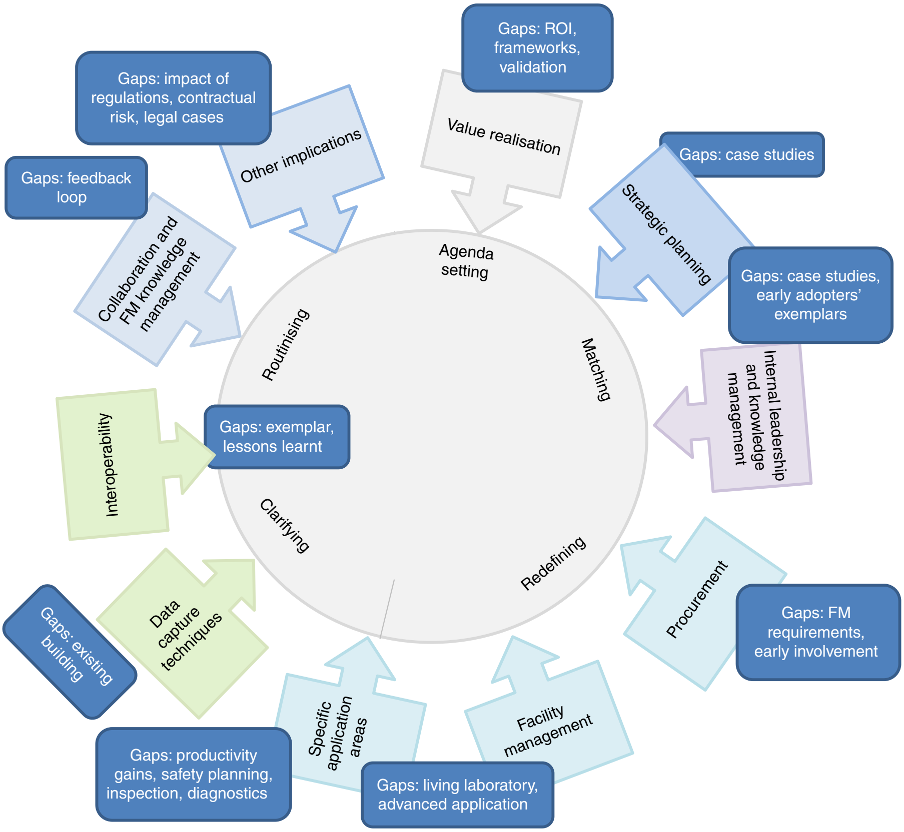

Figure 5.
BIM based FM implementation framework

Innovation diffusion theory (Rogers, 1995) explains the organisational dynamics of the factors affecting technology adoption. The innovation process has five stages under two broad activities: initiation and implementation. Initiation comprises the entirety of information gathering, conceptualising and planning processes for the adoption of an innovation leading up to the decision to adopt it. This has two sub stages: first agenda setting, and second matching. At the agenda setting stage, the organisation deals with general organisational problems that may create a perceived need for innovation. During the matching stage, the organisation deals with fitting a problem from the organisation's agenda with an innovation. Implementation comprises all of the actions, events, and decisions involved in putting an innovation into use. Implementation has three sub–stages, which follow on directly from the initiation sub-stages: third redefining/restructuring, fourth clarifying, and fifth routinising. During the redefining/restricting stage, the innovation, is modified and re-invented to fit the organisation, and organisational structures are altered. During the clarifying stage, the relationship between the organisation and the innovation is defined more clearly. Routinising is the final stage of implementation, during which the innovation becomes an ongoing element in the organisation's activities, and loses its identity.

It can be clearly identified that value realisation and strategic planning both happen during the initiation phase of the organisational innovation adoption stages (Rogers, 1995). Value realisation happens in the agenda setting stage, while strategic planning and internal leadership and knowledge management should occur in the matching stage. However, the other areas

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evolve as the organisation enters into each of the sub-stages of implementation: redefining, clarifying and routinising. Despite this, the procurement, FM, specific application areas, data capture techniques, interoperability, collaboration and FM management areas can all be identified in an organisation which has already implemented BIM in FM.

Longitudinal analysis has revealed that even though case studies have been reported since 2007, none has reported on successful early adopters' implementation strategies, covering research areas such as ROI, strategic planning, internal leadership and knowledge management, and procurement.

Value realisation in the initiation stage. Under innovation diffusion theory, "relative advantage" (Rogers, 1995) refers to the level of benefit to an organisation as is a key factor for early decision-making. Value propositions were reasonably well explored in the literature. However, ROI analysis, required at the initiation stage (Rogers, 1995), was not investigated. Case studies of adopters in the early initiation stages have indicated that justifying ROI is a challenge (Shen *et al.*, 2016). The long period of time needed to realise the benefits of BIM is also reported as a challenge. These challenges call for a shared knowledge base from early adopters and standard protocols from the industry. Even though a theoretical framework has been proposed (Love *et al.*, 2014), there is also a research gap in the area of validating such ROI analysis through real-world cases. For example, analysis of case study organisations, which justify the investment on the basis of both ROI and intangible benefits, and the validation of the benefit realisation frameworks through real-world case projects, will significantly assist the research community, as well as the industry.

Leadership and knowledge management in the initiation stage. Literature analysis revealed that organisational-level factors and individual (leader) characteristics (Rogers, 1995), like leadership and knowledge management, were less explored and demonstrated in case studies. It is worthwhile to explore where BIM adoption is placed among organisational strategic priorities, which is a key influential factor (Edirisinghe *et al.*, 2016; Shen *et al.*, 2016) for early decision-making. Particularly, the variations of organisational priorities for BIM adoption in FM among organisations with varying core businesses, such as education, healthcare, FM, etc. is unknown. It is vital that the knowledge base and experiences of early adopters' decision-making process be shared to exemplify the lessons learnt.

Strategic planning and procurement. FM requirements. Erdogan *et al.* (2010) argue that "user-centred IT" should be developed for the construction industry. In their view, many of the promises to meet the needs and enhance the experience of ICT systems in the industry remain unfulfilled. We argue that a major part of the problem is the fact that industry practitioners are not involved early enough in system development so that the researcher can capture the requirements thoroughly. Thus it is vital to conduct a thorough FM requirement analysis prior to implementation of any BIM prototype for FM.

Early involvement. It is also vital to understand the value of facility maintenance and operation personnel's early involvement in realisation of projects. We recommend that knowledge management (Lindkvist, 2015) strategies should be considered during the strategic and implementation planning stages so that the early involvement for FM can contribute to the optimisation of the process. It is first recommended to have a procurement plan to select service providers and project teams, and to introduce contract terms and requirements to define BIM for FM deliverables.

Apart from the work by Chunduri *et al.* (2013), there has been no research conducted on validating the strategic planning guides, implementation planning guides, and procurement planning guides. However, prototyping and testing these guides in real-world projects and sharing the knowledge is critical to demonstrate the feasibility of these concepts and technologies.

Implementation stage. Specific FM applications in a living laboratory: BIM-related "specific FM application areas" were widely studied and prototyped at the level of

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individual functions. However, a gap exists in the form of a real-life system with communities and settings similar to a 'living laboratory', which is a critical resource for the community of practice as well. A case study building having these application areas integrated through a single source of truth to serve as a user-centred, open innovation BIM ecosystem integrated with other operational systems is a need.

For a wider adoption of BIM in FM, the downstream use of BIM by sub-contractors is required. This is an integral part of the clarifying and routinising stages, in which the organisation achieves full technological maturity. Research suggests that up-skilling contract workers who have low educational attainment and literacy levels (Edirisinghe and Lingard, 2016) to use the innovative and disruptive technology such as BIM is a challenge (Shen *et al.*, 2016). The analysis revealed that the 'Collaboration and FM knowledge management' area is under-researched. There are also few case studies in the literature on this area. Collaboration and FM knowledge management form a feedback loop in the implementation life-cycle, but this has not been well explored. As the downstream use of BIM in FM increases, and upcoming policies for BIM use for FM come into effect, it can be expected that these research areas will grow.

Overall, little research has been done on the three sub-stages of the implementation stage of innovation maturity. For example, none of the research studies report the full maturity cycle of innovation covering the redefining, clarifying and routinising stages of BIM in FM, particularly due to the infancy of adoption. Sharing the success stories of industry leaders and early adopters, either to showcase them as exemplars, or to share the lessons learned throughout these implementation stages, is vital to the wide spread of BIM adoption for FM. This knowledge base is a value-added centrepiece of research for practitioners, and will also give laggards a chance to catch up. Best practice (Sabol, 2008), as well as lessons learnt (Korpela and Miettinen, 2013), should be equally valuable for the research community, as well as to industry followers.

Other open research challenges and the road ahead

This analysis has revealed that legal and policy frameworks have been under-researched relative to other aspects of BIM in FM. In the technical domain, interoperability has been widely explored, but not data capture techniques, which are known to be challenging (Shen *et al.*, 2016; Volk *et al.*, 2014) for FM adoption for existing buildings. It is also interesting to note the little emphasis placed on the application areas of safety planning, inspection and diagnosis in the state of the art. BIM-enabled inspection needs attention, too, because it is an integral element of ongoing preventive maintenance. In summary, procurement, and the legal and policy frameworks are the areas that call for research on BIM-enabled FM. Safety planning, inspection and diagnostics are the BIM-based specific FM applications that need to be explored more thoroughly.

Specific FM applications and productivity gains. BIM-related "specific FM application areas" have been widely studied and widely prototyped. However, the productivity improvements achievable through these models have not been widely explored.

While studies (Taylor and London, 2011; Shan *et al.*, 2012) report productivity gains from the adoption of BIM in the construction phases of case study projects, there is a research gap in the investigation of the productivity gains of using BIM in FM. For example, a real-world project, City of Dreams Casino in Macau (Taylor and London, 2011), reported a significant productivity improvement in time efficiency, and in cost of HVAC following the adoption of BIM. The reduced time was mainly due to the minimisation of reworking, as evidenced by the only 43 hours of reworking compared to the 25,000 anticipated total hours for the entire project. In contrast, the reduced cost was mainly due to labour savings. In this regard, the HVAC contractor projected labour savings of over 4.5 per cent (US$400 K) on the

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HK$9.04 million guaranteed maximum price contract following the adoption of BIM. It is important to analyse such tangible savings during the FM phase as well, and to link this back to the whole of life-cycle of the project. Shan *et al.* (2012) also reported a 38 per cent reduction of work hours following the implementation of a BIM model-based steel connection system compared to a conventional steel connection construction methodology. It is vital to have similar case studies in BIM-enabled FM to demonstrate its value. With the exception of the study by Orr *et al.* (2014), none of the studies reviewed attempted a cost-benefit analysis of the implementation of BIM-enabled FM. It is vital to prototype such models to demonstrate the savings or productivity improvements achievable compared to the traditional methods.

Advanced applications in FM. Edirisinghe *et al.* (2013, 2015) argue that building maintenance strategies should be proactive rather than reactive. These include predictive maintenance strategies. Thus, more advanced deterioration prediction models such as the gamma process (Edirisinghe *et al.*, 2013) and the Markov model (Edirisinghe *et al.*, 2015), have been developed to achieve proactive decision-making for better BM. They also argue that these preventive and predictive FM systems should be developed with an understanding of future needs. With the exponential growth of context-aware pervasive computing systems, future FM systems are envisaged to be embedded with intelligence. Hence, BIM-enabled FM software, middleware, and applications are expected to have more powerful computation, analysis, storage, visualisation, analytics, and cloud computing capabilities. According to Moore's law (Schaller, 1997), with the advancement of the electronic industry producing ever faster, smaller and cheaper transistors, processing power, performance increase and energy efficiency increase and cost decreases, making digital engineering systems, such as BIM-enabled FM, much more advanced, intelligent and proactive. Similarly, according to the predictions by CISCO, the big data doubles every two years. The future BIM-enabled FM will be proactive in decision-making, more dynamic, and linked with various systems, such as automated monitoring, big data analytics, and will have automated, adaptive and proactive decision-making.

Legal aspects. The legal rights of facility owners and FM operators in the event of incorrect information being provided to them in the BIM model remain unclear, and legal cases on such matters are yet to emerge. The legal impact of incorrect information in a BIM model on FM professionals' ability to meet their contractual obligations under an FM contract is unknown (Chew and Riley, 2013). According to a recent survey, the existing forms of contact used in the industry, and the approaches taken to contracting, are not fit for purpose in a BIM-enabled world (BIM+, 2016). Concerns include risks around liability, indemnity and insurance, and intellectual property. Although accepted default BIM contracts or standards are a gap for the whole AEC industry, there are many unresolved challenges and issues specific to FM.

Regulations and BIM adoption. The debate on the influence of governmental or organisational policies on BIM adoption is beyond the scope of this paper, but it opens up an interesting path for future research to investigate the motivations of organisations for using BIM for FM. Researchers have argued that BIM adoption can be fostered by national and state-level policies (Manley and Mcfallan, 2006; Edirisinghe and London, 2015), and by rewards (Gu and London, 2010) and subsidies (Singapore Government, 2015). Standards and guides were implemented internationally. The impact of these standards and guidelines on BIM adoption is unknown. As Müller (2015) points out, an internationally oriented evidence base, and comparative research on the influence of policy-making and implementation on BIM adoption are under-researched areas in the understanding of the use of BIM, not only in the AEC industry, but also in FM.

Despite, the only comparative BIM adoption data available globally is a commercial survey (McGraw Hill, 2014). The sampling method is undisclosed in this potentially biased

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survey, which was sponsored by a BIM software developer. Thus it would be very valuable for the research community to develop an internationally oriented, unbiased evidence base to understand levels of BIM adoption for FM. For example, it is worth studying the impact of policies together with the adoption data in countries such as Singapore and the UK once the policy on BIM for FM has been implemented.

Policy-led vs Industry-led adoption. We argue that organisational BIM-enabled FM adoption should be studied in greater depth, and that consideration should be given to its motivations. Organisations might use systems, in part because of intrinsic motivators. Deci (1975) defined intrinsic motivators as "the activities that people seem to engage in for their own sake and not because they lead to an extrinsic reward". According to Davis (1989), people enjoy the process of using an information system (and thereby gain intrinsic reward), not just because they are being extrinsically rewarded for the consequences of usage. Real-world case studies should be conducted on motivations for the use of BIM-enabled FM.

Adoption of BIM for FM should also be investigated in countries representing a spectrum of national and state/provincial-level policies, varying from powerful mandating policy to laissez faire approaches, to understand the real motivation for early adopters in the absence of a centralised policy. In this regard, it is also noteworthy to evaluate the motivations of early adopters in the USA and other countries. These may reveal the answers to open research questions such as:

RQ1. Does the policy influence the adoption of BIM-enabled FM?

RQ2. Does the policy promote innovation in BIM-enabled FM?

RQ3. Should the innovation be industry-led rather than government-led?

RQ4. What should the international code of practice be for multi-national projects when national BIM policies are available?

6. Conclusions

Although BIM is capable of supporting FM in theory, convincing results of the full use of BIM-enabled FM in practice are yet to emerge. Given that, this review paper attempts to understand the optimistic use of BIM in FM practice. This study identified the significant aspects of BIM-enabled FM based on reviews of a large pool of both academic and industry-based articles. The results captured benefits and challenges. Thematic analysis of research articles identified main and sub-research areas in the BIM-enabled FM implementation lifecycle. The articles were also analysed to understand the variation in research interest over the years. The main research areas identified are: value realisation, strategic planning, internal leadership and knowledge management, procurement, FM, specific application areas, data capture techniques, interoperability, collaboration and FM knowledge management, and other implications.

The classification identified by the thematic and holistic analysis of the articles was mapped on to the stages of innovation diffusion theory. This enabled a framework for BIM for FM implications to be defined, as well as to identify further research challenges.

The study proposes three main further research areas: specific FM applications and productivity gains; advanced applications in FM; and regulations and BIM adoption. Well-researched areas of specific BIM applications require verification of value realisation analysis. Once organisations reach a mature level of technology diffusion it is vital that the productivity grains of BIM implementation be examined. As a destructive technology, the learning curve of BIM can be years long, and true productivity gains cannot be realised till an organisation reaches maturity. In relation to preventive, predictive maintenance and intelligent replacement decision-making (Edirisinghe, Setunge, and Zhang 2012), future BIM-enabled FM models will be proactive in decision-making, more dynamic, and linked with various systems, such as automated monitoring and big data analytics. The influence of governmental or organisational policies on BIM-enabled FM has also not been adequately studied; future research requires the conduct of an impact analysis on this matter.

This framework enables FM practitioners to identify the stages of the FM implementation life-cycle, and the gaps identified open paths for future research.

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Corresponding author
Ruwini Edirisinghe can be contacted at: ruwini.edirisinghe@rmit.edu.au

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