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Moving from building information models to digital twins for operation and maintenance

Qiuchen Lu PhD

Research Associate, Institute for Manufacturing, University of Cambridge, Cambridge, UK

Xiang Xie PhD

Research Associate, Institute for Manufacturing, University of Cambridge, Cambridge, UK (corresponding author: xx809@cam.ac.uk)
(Orcid:0000-0003-4601-9519)

Ajith Kumar Parlikad PhD

Reader, Institute for Manufacturing, University of Cambridge, Cambridge, UK (Orcid:0000-0001-6214-1739)

Jennifer Mary Schooling PhD

Director, Centre for Smart Infrastructure and Construction, University of Cambridge, Cambridge, UK

Eirini Konstantinou PhD

Research Associate, Institute for Manufacturing, University of Cambridge, Cambridge, UK (Orcid:0000-0003-3652-5557)

With the rising adoption of building information modelling (BIM) for asset management within the architecture, engineering and construction sectors, BIM-enabled asset management during the operation and maintenance phase has been increasingly attracting more and more attention in both research and practice. This paper provides a comprehensive review and analysis of the development of state-of-the-art research and industry standards that impact on BIM and asset management within the operation and maintenance phase. However, in the aspects of both information richness and analytical capability, BIM is not always enough in delivering effective and efficient asset management, particularly in the operation and maintenance phase. Therefore, a framework for future development of smart asset management is proposed, integrating the concept of digital twins. Digital twins integrate artificial intelligence, machine learning and data analytics to create dynamic digital models that are able to learn and update the status of the physical counterpart from multiple information sources. The findings will contribute to inspiring novel research ideas and promote widespread adoption of digital-twin-enabled asset management within the operation and maintenance phase.

1. Introduction

Computerisation and digitisation are emerging to have a wide impact on the way that the life cycle of physical/engineering assets is managed (Parn *et al.*, 2017). It is predicted that artificial intelligence (AI) could add 10% to the UK economy by 2030 (NIC, 2017). Additionally, improved data sharing and data utilisation could result in lower consumer bills, reduced impact on the natural environment and realise smart asset management. Particularly, advances in building information modelling (BIM) is likely to aid in reducing the time for updating databases in the operation and maintenance (O&M) phase by 98% (Ding and Drogemuller, 2009). The necessary technologies and approaches are more or less already available. However, data need to be stored, shared and analysed safely and securely, and therefore, technologies must be developed to ensure both security and efficiency.

Achieving a comfortable living environment and smart building management is a complex issue in the O&M phase, which costs around 80% of whole life-cycle cost. Comprehensive information needs to be recorded and multiple stakeholders would be involved. The process of asset management in the O&M phase is required to maintain integrity, validity and interoperability (Wetzel and Thabet, 2015). Consequently, an effective and intelligent asset management system is needed to maintain dynamic information, support various activities and contribute to a comfortable environment (Lu *et al.*, 2018). Various tools and systems have been implemented to enhance O&M management, such as computerised maintenance management systems (CMMSs), computer-aided facility management (CAFM) systems, building

automation systems (BASs) and integrated workplace management systems (Sapp, 2015). For instance, CMMS is a computerised system for O&M management, which can record daily work orders, historical records, service requests and maintenance information. However, it still requires significant effort and time for facility management (FM) professionals to extract the diverse O&M information that they need (Wetzel and Thabet, 2015). Thus, there is still a lack of an integrated platform that could manage information distributed in different databases and support various activities in the O&M phase.

BIM, as a digital representation of a building or civil infrastructure asset, can be extended to form the basis for a database of all assets and facilitate the exchange of information in a unified and digital manner (Eastman *et al.*, 2011). Moreover, in the O&M phase, BIM can be used as an information source and a repository at the same time, supporting various activities in existing buildings and infrastructure (Volk *et al.*, 2014). BIM has been successfully adopted in the design and construction phases. However, BIM still has limited adoption within asset management (Lu *et al.*, 2018; Volk *et al.*, 2014). The research related to BIM and asset management in O&M is still at its infancy but is rapidly growing (Pishdad-Bozorgi *et al.*, 2018).

BIM has proven to reduce information loss significantly during O&M management (Lu *et al.*, 2018). In particular, BIM can integrate various digital products and asset data within a comprehensive digital platform – namely, a semantically rich integrated model, which manages different data resources

effectively and efficiently (Succar, 2009). Thus, integration and interaction based on BIM can be achieved through model server technologies, single integrated/distributed federated databases, software-as-a-service solutions, Internet of things (IoT), sensor systems and so on (Bentley and Workman, 2003; Succar, 2009; Volk *et al.*, 2014; Wilkinson, 2008). Hence, BIM and its integration properties become extremely invaluable to asset management in the O&M phase that is aimed at obtaining long-term value and improving efficiency through implementing smart technologies and approaches. Indeed, the development of smart BIM-enabled asset management in the O&M phase has an immense potential towards improved collaboration by way of an intelligent, efficient, interoperable and integrated platform.

Various integrated and comprehensive solutions for asset management in the O&M phase have been proposed by adapting BIM and developing systems to improve interoperability and integration. For instance, Motawa and Almarshad (2013) proposed a case-based-reasoning (CBR)-integrated BIM system for building maintenance to improve the efficiency of decision-making and communication among different stakeholders. The restoration team of the Sydney Opera House also designed a unified central data repository integrating different resources to support effective O&M management. However, it still lacks a detailed data capturing and maintenance approach (Ding and Drogemuller, 2009; Parsanezhad and Dimyadi, 2014). However, an integrated intelligent platform that can help monitor, update, communicate and integrate O&M management issues in tandem is still waiting for continuous development and improvement.

Besides depicting the state-of-the-art implementation BIM in asset management, this paper discusses the benefits and limitations of current research and standards in asset management and potential developments towards digital twin (DT)-enabled asset management in the O&M phase. DT refers to an integrated multifaceted and multiscale digital replica of physical assets, processes and systems (Kang and Hong, 2015). In the context of Digital Built Britain (DBB), a DT is ‘a realistic digital representation of assets, processes or systems in the built or natural environment’ (CDBB, 2018). From the perspective of information richness (as shown in Figure 1) and analytical capability, the concept of DT is broader than BIM. In this sense, DT not only is a model of the physical object or system, which connects between digital and physical assets, but also transmits data in at least one direction and monitors the physical system in real time. Moreover, DTs also support analytics, control and simulation functions (Peng *et al.*, 2017).

Consequently, this study will focus on analysing the literature on asset management in the O&M phase, including FM O&M management, which commonly appear in publications and standards, at the building/infrastructure level (as shown in Figure 2). The hierarchical architecture of DT-enhanced asset management framework is proposed in this paper, which presents insight into the new field of DT-enabled asset management in the O&M phase.

Figure 1. Classifications of BIM and DT

Figure 2. Research scope of this study

2. Current research of BIM-enabled asset management

Considering BIM for asset management, a bunch of academic publications were reviewed. The literature search was conducted on three academic databases (Scopus, ScienceDirect and Web of Science) that had been chosen for their comprehensive coverage on engineering and computation in construction and which cover a large number of journal and conference publications. The search was restricted to the application of BIM for asset management in O&M/FM. Numerous recent developments not only focus on implementation and research in BIM-enabled asset management areas from technical aspects (Aziz *et al.*, 2016; Gray *et al.*, 2013) but also put great efforts in improving the performance of asset management in the O&M phase from the perspective of management and organisation (Akbarnezhad *et al.*, 2014; Chotipanich, 2004). These improvements can be classified as technology-related issues, information-related issues and organisation-related issues (Alvarez-Romero, 2014; Volk *et al.*, 2014).

The effectiveness of asset management in the O&M phase will heavily rely on continuous information on asset conditions and performances, reliable communication channels and properly documented professional knowledge from previous experience (Alvarez-Romero, 2014; Lu *et al.*, 2018; Parn *et al.*, 2017). Obviously, BIM would aid in overcoming some of the complex problems in the O&M phase (Love *et al.*, 2015; Sabol, 2008). Building/infrastructure-related information can be directly or indirectly integrated within available digital technologies in a BIM-enabled environment. As shown in Table 1, many researchers have focused on developing BIM-enabled asset management systems facilitating high-performance O&M. Targets and benefits of current BIM-enabled asset management during O&M can be summarised as follows

- accurate and efficient support for decision-making, monitoring and communication

- easy retrieval and storage of maintenance, inventory, warranty, installation and operation data
- enhanced collaboration and increased visualisation for stakeholders
- effective management and planning of orders, activities, schedules, labour and space
- convenient maintenance and tracking of assets
- optimised use of fuel, utilities and materials
- facilitation of emergency evacuation planning.

The existing asset management approaches to integrating new technologies, information and further embracing organisational issues is a major challenge (Wong *et al.*, 2018). Although a large amount of effort has been made in BIM-enabled asset management, the key problems to its current implementation and research are still unsolved. The reasons can be the lack of awareness of the potential benefits of smart assets (e.g. BIM) to

Table 1. Brief summary of BIM-enabled asset management development

Author (year)	Data sources	Algorithms	Key contribution
Shen <i>et al.</i> (2012)	Wireless sensor/RFID-based real-time asset tracking, BIM	Agent-based web services	Presenting a conceptual framework of the agent-based service-oriented integration approach for facility life-cycle information integration
Dibley <i>et al.</i> (2012)	Sensor, IFC	Ontology development including sensor and building ontology	Presenting an intelligent multi-agent software framework (OntoFM) supporting real-time building monitoring
Lee <i>et al.</i> (2013)	Sensor, BIM, GIS, ubiquitous sensor network, urban object identification	Integration of facility-related information and integration of management functions	Presenting intelligent urban FM for real-time emergency response
Ko <i>et al.</i> (2013)	RFID, web-based system, database	Four-layer fuzzy neural network model, scheduling theory	Developing a web-based RFID FM system for enhancing FM efficiency
Lin and Su (2013), Lin <i>et al.</i> (2014)	Mobile, barcode, database, BIM	An information centre for data querying	Proposing a mobile automated BIM-based FM system for FM staff in the O&M phase
Motamedi <i>et al.</i> (2014)	CMMS, Cobie, IFC, BIM	Data integration by way of connecting unique IDs; knowledge capture using fault trees	Providing a knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in FM
Kang and Hong (2015)	GIS, BIM, IFC, CityGML	BIM/GIS-based information extract, transform and load architecture	Proposing a software architecture for the effective integration of BIM into a GIS-based FM system
Róka-Madarász <i>et al.</i> (2016)	CAFM, CAD, database	Top-down object hierarchy; geometric description language	Elaborating a methodology for gathering building O&M cost data
Shalabi and Turkan (2016)	BIM, IFC, BEMS, BAS	A schema that enables the integration of data; a process linking alarm reports of equipment failures with IFC BIM	Proposing an automated process that responds to alarms by retrieving alarms reported by FM systems for corrective maintenance
Peng <i>et al.</i> (2017)	Data warehouse, BIM	Clustering algorithm; cluster-based frequent pattern mining algorithm	Proposing a BIM-based data mining approach for extracting meaningful patterns and detecting improper records
Arsalan <i>et al.</i> (2017)	BIM, sensor	Hadoop; distributed storage	Developing a proactive safety FM system
Suprabhas and Dib (2017)	BIM, sensor, Cobie	Data integration and visualisation	Developing an application that integrates sensor data and reports the data by way of the virtual model of the building
Hu <i>et al.</i> (2018)	BIM, GIS, BAS, web service, QR code/RFID	Logic chain generation algorithm; equipment identification and grouping algorithm	Developing a cross-platform mechanical, electrical and plumbing management system
Chen <i>et al.</i> (2018)	BIM, IFC, FM systems	An algorithm used for optimal maintenance path planning; Dijkstra algorithm used for maintenance scheduling	Proposing a BIM-based framework for automatic scheduling of facility maintenance work orders

BEMS, building energy management systems; CAD, computer-aided design; Cobie, Construction Operations Building Information Exchange; GIS, geographic information system; Hadoop, highly archived distributed object-oriented programming; IFC, Industry Foundation Classes; RFID, radio-frequency identification devices

the O&M phase (Codinhoto and Kiviniemi, 2014; Lu *et al.*, 2018), the lack of demonstrators in the real world of BIM-enabled asset management implementations (Becerik-Gerber *et al.*, 2011) and the lack of a well-organised framework to design customised asset management in the O&M phase.

Integration of different technologies and enlarging their intellectual capabilities are suggested to develop benchmarks corresponding to different use case scenarios. How to collect, store, manage and maintain various data resources (including FM systems), and to process the collected huge volume of data for making decisions effectively and intelligently, is all needed to be studied systematically in future research. There is still a lack of practical decision-making algorithms applied to predict and locate failure issues in daily asset management. According to Matarneh *et al.* (2019), a high growth rate of publications is shown in optimising O&M management. However, the realisation of CBR modules is applicable only to certain scenarios, due to the oversimplification of mechanisms. Thus, improvement in the reliability and generalisation of technology and integration of information is an indispensable step towards smart BIM-enabled asset management for O&M. Moreover, enhancing collaboration and interoperability from organisational views is also crucial in order to eliminate time-consuming manual processes and to facilitate maintenance activities for FM professionals.

3. Industry standards and their scopes

3.1 Overall introduction of industry standards

This section aims to review the current industry standards, specification and guidance as produced by standardisation

organisations and regulatory bodies, in the domains of BIM and asset management. As seen from the last section, the challenge to implementing BIM within asset management is multifaceted, with one of the key challenges being the information capture, exchange, use and management throughout an asset whole life (design, construction, O&M and disposal/renew). As such, it is also a requirement to review data-interoperability-related standards within the scope of BIM and asset management, most notably the exchange of information from the design and construction phase into the O&M phase.

There is an array of standards that focus on BIM and information management processes within an asset's life cycle; the most comprehensive standards have been developed by BSI and ISO. Figure 3 highlights the key standards and specifications as per the associated life cycle. The bulk of the standards focus on the design and construction phase. A few standards that are associated with the O&M phase focus on the exchange of information and geometry from design and construction into the O&M phase and are not specifically focused on using BIM for asset management. Furthermore, there is a strong focus to support the end-user, operator and maintainer engagement at the easy stages within the design phase to capture their requirements.

3.2 Asset management standards

Asset management is a set of management processes and systems that encompass the management of an asset throughout its whole life cycle. This includes management of the physical asset and the related digital information within the context of the organisation. One of the key objectives on implementing an asset management

Figure 3. Summary of standards throughout an asset's whole life

system is the ability to diffuse the traditional organisational siloed effect – for example, the capital works department not consulting the maintenance department for their requirements within new construction work.

ISO 55000:2014 (formally PAS 55/1/2) is a series of standards (three in total) that focus on the development of an asset management system for an asset-centric organisation. The standards are strategic in nature and support the management processes. This includes overview, principles, terminology, requirements and guidance for the application of the asset management requirements. A fundamental goal of asset management involves the balancing of cost, opportunities and risk against the desired performance of assets, to achieve the organisation's objectives. The performance of the assets can be measured in different value requirements, including not just the traditional measurement of financial value but also environmental and social value.

Furthermore, an industry representative body for asset managers in the UK, the Institute of Asset Management (IAM), has developed a collection of guidance documentation in collaboration with the industry to support the development of an asset management system. This guidance includes the development of asset-management-related documentation, developing performance measures, how to make improvements of the concepts and philosophy of asset management.

Table 2 summarises the key documentation related to asset management. The scope of asset management is broad, as it encompasses an asset's whole life and its value within an organisation's context. The standards are strategic in nature and provide a framework with associated processes for the development of an asset management system. While the standards provide the foundation for the development of an asset management system, they are limited in providing technical guidance. First, they fail to incorporate the emerging BIM processes, limiting the use of BIM within the O&M phase of an asset. Second, not an efficient amount of focus is given to the information management process requirements within asset management. Finally, no framework is given that aids in aligning the organisational requirements with the asset information requirements and limiting the value of information that is collected from the organisation's assets.

3.3 BIM standards

BIM is an emerging process of designing, constructing or operating a building or infrastructure asset using digital object-oriented information. The development and implementation throughout the different life cycles of an asset are supported by an array of standards that have been developed by multiple country standard and regulation organisations. Most notably, the BSI has developed a comprehensive array of BIM-related standards focusing on individual life-cycle phases, including design, construction and operation. The BSI BIM-related standards lay

down the foundation for how information should be defined, collected, exchanged, stored, used and disposed within the context of BIM information management processes. While BIM has been widely adopted within the design and construction phase, its adoption within the O&M phase is limited. This is partly due to the multifaceted complex challenges of asset management and the alignment of the asset management frame to the BIM information management processes.

Table 2 summarises the key specifications and standards for BIM and their associated life-cycle phase. As can be seen, the scope of BIM is broad and encompasses the information management processes of an asset's whole life with many stakeholders. While the standards provide the theory and concept of BIM, several limitations are summarised in this paper. First, the concept is well described, but there is no methodology provided for implementation. Second, due to the broadness of BIM, the standards and specifications often lack technical details. Finally, PAS 1192-3 BIM for the O&M phase fails to address the multifaceted challenges within adopting BIM for the O&M phase. The summarised BIM standards have been created in isolation of any organisational management processes and as such fail to address the core processes of asset management (BSI, 2013b, 2014a). Furthermore, they lack support to allow a holistic organisational adoption of BIM, particularly in the O&M phase. This is partly due to the standard's failure of clearly addressing stakeholder requirements within the BIM domain and simplifying the exchange from design/construction into the O&M phase and lack of understanding of how information is used within the O&M phase.

3.4 Data exchange and interoperability standards

To support the implementation of BIM and asset management, there is a fundamental need to standardise the exchange of geometric and non-geometric information among different stakeholders in the O&M phase, and this requirement has resulted in a concept called OpenBIM. OpenBIM is a set of open-source data standards for the exchange of information between BIM authoring and validation tools. Most notably, buildingSmart has aided in developing the open-source data format Industry Foundation Classes (IFC) that supports the exchange of BIM-related information and has been widely adopted by software developers. One of the key advantages of IFC is the interoperability that it enables, supporting the exchange of BIM models between different enterprise software providers. For example, a designer can exchange the IFC model with the quantity surveyor about cost estimation issues without using incompatible native formats. The overall goal of IFC is to support the exchange of information within an open-source standard throughout an asset's whole life, and this broad goal makes it an extensible information model (Shalabi and Turkan, 2016).

Furthermore, Construction Operations Building Information Exchange (Cobie) is the UK government's chosen information exchange schema for BIM-related information, alongside the BIM

Table 2. Brief summary of standards related to asset management, BIM and data exchange and interoperability

Standard type	Standard title	Key focus area	Alignment to other standards	Reference
Asset-management-related standards	ISO 55000: Asset management – overview, principles and terminology	An overview of an asset management system with key principles and terminology	ISO 55001 ISO 55002	ISO (2014a)
	ISO 55001: Asset management – management systems – requirements	Defines the requirements for the development of an asset management system	ISO 55000 ISO 55001	ISO (2014b)
	ISO 55002: Asset management – management systems. Guidelines for the application of ISO 55001	Provides guidance on management processes for meeting the requirements outlined in ISO 55001	—	ISO (2018)
	<i>Asset Management – an Anatomy (IAM)</i>	A coherence industry guidance to asset management within 39 subject areas within six categories	—	IAM (2015)
	<i>The Asset Management Landscape</i>	A framework for enabling knowledge and information compared, analysed and aligned around a common understanding of the discipline of asset management	ISO 5500-1/2	IAM (2014)
	BS 8536: Briefing for design and construction (parts 1 and 2)	Provides recommendation for briefing on the operational requirements during the design and construction phase	ISO 55000-1/2 PAS 1192-2/3	BSI (2015a, 2016a)
	PAS 91:2013: Construction prequalification questionnaires	Provides a common set of questions to be asked of the supply chain to validate whether they can meet the operational requirements	ISO 55000-1/2 PAS 1192-3	BSI (2013a)
BIM-related standards	BS 1192-2007 + A22016: Collaborative production of architectural, engineering and construction information. Code of practice	Development of a design collaboration data environment for the sharing of design-related information	PAS 1192-2/3/5	BSI (2007)
	PAS 1192-2: Specification for information management for the capital/delivery phase of construction projects using BIM	Defines a framework for the development of BIM processes within the construction phase	BS 1192 PAS-1192-5	BSI (2013b)
	PAS 1192-3: Specification for information management for the operational phase of assets using building information modelling	Focuses on the O&M phase of an asset, introducing the concept of an asset information model	ISO 55000-1/2/ BS 1192-4	BSI (2014a)
	PAS 1192-5: Specification for security-minded building information modelling, digital built environments and smart asset management	Framework for a security-minded approach to BIM information management processes as defined within PAS 1192-2	ISO 55000-1/2 PAS 1192-2/3	BSI (2015b)
	<i>Government Soft Landing</i>	Defines a framework for the delivery of information throughout the life cycle of an asset	PAS 1192-3 BS 1192-4 ISO 55000-1/2	Cabinet Office (2013)
Data-exchange-and interoperability-related standards within asset management and BIM aspects	BS 1192-4: Collaborative production of information. Fulfilling employer's information exchange requirements using COBie. Code of practice	Defines an information data schema for the exchange of operation-related information throughout an asset's whole life	PAS 1192-3 ISO 16739 (ISO, 2013)	BSI (2014b)
	ISO 16739: Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries	Open-source and vendor-neutral exchange format for the example of BIM-related geometry and information	ISO 29481 ISO 12006-3 (ISO, 2007)	ISO (2013)
	ISO 29481-1: Building information models – information delivery manual	A methodology that links business processes undertaken with the construction of an asset with the specific information required by these processes	ISO 16739 PAS 1192-3	ISO (2016)
	ISO 29481-2: Building construction – organization of information about construction works – framework for classification	Defines a framework for the development of a classification system within the built environment	ISO 12006-3 BS 1192 PAS 1192-2/3	ISO (2012)
	ISO 12006-2: Building construction – organization of information about construction works – framework for object-oriented information	Defines a framework for the development of an ontology to use within object-orientated design	ISO 12006-2	ISO (2015)
	PAS 212: Automatic resource discovery for the Internet of Things – specification	Design of a service for IoT, widely adopted in practical applications such as smart cities	BS 1192-4 ISO 16739	BSI (2016b)

model and PDF documentation. The purpose is to create a structured approach for the exchange of information throughout an asset's whole life cycle. Cobie is a structured spreadsheet that can be populated by multiple stakeholders (facility manager, supplier etc.) and exchanged with the asset owner at predefined time or event milestones. The O&M information captured within Cobie is a subset of the IFC data model, called a Model View Definition. While Cobie provides a simple and user-friendly approach (through spreadsheets) to the exchange of information throughout many stakeholders within an asset's life cycle, it is limited as a central validation process and risks information being lost within multiple spreadsheets, in comparison with a centrally controlled database/platform. Furthermore, the data entities, types and parameters required for FM using IFC and Cobie are still limited. More complicated data types in the O&M phase are needed (Hamledari *et al.*, 2017; Motamedi *et al.*, 2014).

3.5 Findings

While, there is a growing set of standards that aim to enable the development of BIM within O&M and asset management, there is a fundamental lack of a framework to support this development. Most notably, there are no holistic overarching frameworks that support the alignment of strategic, process and technical standards. This is witnessed within the standard for classification of built environment assets (ISO 12006-2), as this standard does not align to the information management processes for the built environment assets (BSI, 2014a; ISO, 2014a).

Furthermore, the standards have often been developed for individual life cycles and disciplines, resulting in limited usage throughout the whole-life cycles, as can be witnessed within the limited IFC classes and property sets that have limited support for infrastructure projects and O&M requirements. Finally, there is a lack of the understanding of the organisational context of asset owners. While ISO 55000 supports the development of management processes within asset management, it does not align to information management processes such as PAS 1192-3 or ISO 12006-2, therefore creating a disconnection from the organisational context and information management processes for their built environment assets.

4. Limitations of BIM-enabled asset management in O&M

Many organisations and researchers have made significant efforts to accelerate the development of BIM-enabled asset management in the O&M phase from technology, information, organisation and standard perspectives. There are still many issues that need to be addressed to meet the anticipation of effective and efficient O&M (Ding *et al.*, 2009; Lu *et al.*, 2018; Motamedi *et al.*, 2014; Volk *et al.*, 2014). Based on the preceding analysis, corresponding limitations and gaps are still needed to put forward from these four perspectives. Table 3 provides a comprehensive summary of limitations and gaps in current research and standards for achieving smart asset management in the O&M phase.

Table 3. Limitations and gaps of current research and standards for developing smart asset management in O&M phases

Technology-related issues	<ul style="list-style-type: none"> ■ Lacking a well-organised demonstrator and guideline for technology selection, design and integration ■ Lacking integration of BIM with various CAFM systems ■ Lacking integration of BIM with other systems – for example, locating and navigating in a complex BIM environment is difficult when barcoding/tags are not properly linked with BIM ■ Lacking integration among various applied systems ■ Lacking clear and logical plans for updating as-is BIM
Information-related issues	<ul style="list-style-type: none"> ■ Lacking a predefined strategy of transforming different information – for example, natural languages, expert experience and digital data ■ Lacking a customised and extensible database for different types of information ■ Information aspects in the CAFM systems not matching those in the BIM-authoring tools ■ Lacking clear defined strategies for information saving, exchanging and sharing ■ Lacking specifying LOD requirements for BIM in the O&M phase ■ Lacking specific information requirements according to the organisational roles
Organisation-related issues	<ul style="list-style-type: none"> ■ Lacking knowledge of specifying requirements of asset management early in the design phases ■ Lacking understanding of learning processes for BIM in maintenance in the early building project stage ■ Lacking an updated management mode (including people and facilities) for smart BIM-enabled asset management in the O&M phase ■ Lacking updated working and services workflows for smart BIM-enabled asset management in the O&M phase ■ Querying and updating routines are usually manual and time-consuming ■ BIM and systems are not fully integrated with the asset management workflows
Standard-related issues	<ul style="list-style-type: none"> ■ Lacking a recognised standard/ specification determining the specific data requirements, BIM implementations, management processes and strategies in a comprehensive view ■ Standards have often been developed for use within individual life-cycle stages and disciplines, resulting in discontinuity throughout the asset's whole life ■ The developed standards are often generic in nature and fail to address the particular implementation challenges ■ There is little to no alignment between the different standards, resulting in strategic documentation that does not align to process or technical requirements

LOD, level of details

5. A framework for enhanced DT-enabled asset management in the O&M phase

With the basis of comprehensive analysis and limitations, this paper proposes the hierarchical architecture of the DT-enabled asset management framework. In daily O&M management, compared with BIM, DT is more suitable for complex and comprehensive data management considering the limitations of BIM listed earlier because DTs are built on data and have the capacities of integrating various data resources.

The development of DBB will further accelerate benefits and development of BIM and other digital technologies in the asset management sector based on the momentum created by former efforts. Furthermore, as an authoritative guidance to both researchers and engineers, the report data for public good released by the UK National Infrastructure Commission states that '[t]he UK needs a digital framework for data on infrastructure to harness the benefits from sharing better quality information about its infrastructure; how it is used, maintained and planned' (NIC, 2017: p. 53). Hence, the DT is widely promoted. DT is a digital model that is a dynamic representation of an asset and mimics its real-world behaviours. DT is built on data. However, in research on DTs, a clear-defined and well-organised framework is still needed to supervise their current implementations, identify gaps and provide road maps for future development. Moreover, without

such a framework, they are susceptible to omitting some possible improvement and key limitations.

Through a comprehensive literature review, the authors propose a framework for DT-enabled asset management in the O&M phase. From a practical viewpoint, four aspects of requirements, intelligence, efficiency, integration and interoperability need to be considered for successful implementation of DT-enabled asset management. Intelligence means shifting from traditional manual and labour-intensive asset management to more active and automated approaches (e.g. automatic monitoring process, data-driven approaches and knowledge-led methods). Efficiency means the ability to manage assets in the O&M phase using effective ways with fewer resources required (e.g. time, cost, FM professionals and computational cost). Integration addresses that all assets (including data, technology and models) can be compatible, integrated and further collaborative. Interoperability describes how DT-enabled asset management can coherently deal with various activities and seamlessly co-operated with other systems/people.

Key layers of achieving 'smart' DT-enabled asset management are summarised and presented in Figure 4.

- Smart asset layer. The term 'smart asset' refers to conducting asset management activities with high performance, such as

Figure 4. Potential framework of DT-enabled asset management in the O&M phase

digital techniques, as-is BIM and information and communication technology, and further has capacities co-operated with other assets. These smart assets will increase productivity in terms of their operational efficiencies in daily services. Due to technological advances (e.g. image-based techniques), contactless data exchange (e.g. radio-frequency identification (RFID)), distributed sensor systems, wireless communication and mobile access (e.g. Wi-Fi environment) are all available in the O&M phase. Smart assets would be of immense importance for real-time data collection, effective communication and close integration with other assets. Moreover, as-is BIM models will be the central platform linking with different databases and systems in this perspective framework. An as-is BIM is used to describe the up-to-date BIM in the O&M phase.

- Smart asset integration layer. With the support of smart assets, there is a need to have a layer providing integration and intraoperative services. IoT (including RFID, QR code, sensor systems and network technologies) can support seamless sensing and actuating devices to share information by way of a predefined framework and wireless technologies. Its framework is realised through ubiquitous sensor systems, data analysis, information representation and cloud computing. In the smart asset integration layer, IoT (including RFID, QR code, sensor systems, cloud computing and network technologies) provides open access to various selected subsets of data from their corresponding digital services and supports extensible innovative applications. This layer also can connect assets (including involved people) into interactive and intelligent entirety.
- DT-enabled asset management layer. Successful development of DT-enabled asset management can be achieved from the following four aspects: (a) a clear and well-defined framework for DT-enabled asset management – namely, the perspective framework; (b) an intelligent and seamless plan of integrating all assets during management processes – namely, smart assets and smart asset integration layer; and (c) a practical interoperability method for exchanging and storing information between DT and various FM systems/people – namely, the DT and AI-supported decision-making systems. DT will be introduced into this framework. It refers to an integrated multifaceted and multiscale digital replica of physical building/infrastructure, processes and systems. In this framework, the DT integrates IoT, AI, machine learning and existing software analytics with required data to create a dynamic digital platform that updates as-is conditions following the physical building/infrastructure asset. As-is conditions express the current conditions of assets, including work orders, operational information records, FM professional in charge, up-to-date maintenance information and status. Moreover, AI-based intelligent systems would keep learning from experts with rich asset management knowledge for effectively making decisions about daily events and emergency issues. The final aspect is (d) an effective and efficient communication, co-operation and management system for users and FM professionals. For instance, site

workers are required to be trained properly to understand the technologies and use the tools developed.

In general, this perspective framework is developed to depict the meaning of DT-enabled asset management. Furthermore, it also provides a consolidated framework for both researchers and practitioners involved in DT or asset management to have a more detailed understanding of how to achieve DT-enabled asset management in the O&M phase.

6. Conclusions

With the extensive attention to implementations of smart asset management in the O&M phase and the expectations to take all the advantages of BIM and digital techniques in asset management, this paper provides a comprehensive review and analysis, covering both academic publications and industry standards. In order to present the insight into the new field of DT-enabled asset management in the O&M phase, this study gives an overview of academic publications related to BIM-enabled asset management and associated industry standards by summarising various works in different areas and provides possibilities to achieve the goal of transforming to DT-enabled asset management. Detailed limitations and knowledge gaps are discussed, and a perspective framework is also presented. Furthermore, it is also clear that more efforts should be made based on the proposed perspective framework. This effective improvement is an important concern because all assets should be incorporated and integrated seamlessly. Moreover, DT and AI-supported decision-making systems would highly improve the intelligence and integration of the whole system. From the standard aspects, effective and efficient communication, co-operation and management mode would be a close linkage between people and processes.

Future works are, however, needed to do the following: (a) Based on the perspective framework, further the detailed concepts and a case study in real practice of DT-enabled asset management will be developed. (b) DT-enabled asset management at building/infrastructure will be extended to city-level development; (c) Research should be conducted to investigate the alignment of the proposed framework with the emerging domain of smart cities, specify aligning smart assets with smart cities. (d) The interaction and impact of a smart asset with diverse stakeholders (including customers and the general public) need to be understood better.

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