Moving from Building Information Models to Digital Twins for Operation and Maintenance

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Manuscript title: Moving from Building Information Models to Digital Twins for Operation and Maintenance

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Abstract

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 state-of-the-art research and industry standards development that impact upon 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, especially in 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 operation and maintenance phase.

1. Introduction

Computerisation and digitisation are emerging to have a wide impact on the way the lifecycle 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 utilization could result in lower consumer bills, reduced impact on the natural environment and realize smart asset management. Particularly, advances in building information modelling (BIM) is likely to aid in reducing the time for updating databases in operations and maintenance (O&M) phases by 98% (Ding and Drogemuller 2009). The necessary technologies and approaches are more or less already available. However, data needs to be stored, shared and analysed safely and securely, and therefore technologies must be developed to ensure both security and efficiency.

Achieving comfortable living environment and smart building management is a complex issue in O&M phase, which costs around 80% of whole lifecycle cost. Comprehensive information needs to be recorded and multiple stakeholders would be involved. The process of asset management in O&M phases is required to keep the 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 Computerized Maintenance Management Systems (CMMS), Computer-Aided Facility Management (CAFM) systems, Building Automation Systems (BAS), and Integrated Workplace Management Systems (IWMS) (Sapp

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2015). For instance, CMMS is a computerized system for O&M management, which can record daily work orders, historically records, service requests and maintenance information. But it still requires significant effort and time for facilities management (FM) professionals to extract the diverse O&M information 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 O&M phases.

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 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 rapidly growing (Pishdad-Bozorgi et al. 2018).

BIM has been 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 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, SaaS (Software as a Service) solutions, Internet of Things (IoT) and sensor systems etc. (Succar 2009, Bentley and Workman 2003, Wilkinson

2008, Volk et al. 2014). Hence, BIM and its integration properties become extremely invaluable to asset management in O&M phase that aiming at obtaining long-term value and improving efficiency through implementing smart technologies and approaches. Indeed, the development of smart BIM-enabled asset management in O&M phases has an immense potential towards improved collaboration via an intelligent, efficient, interoperable and integrated platform.

Various integrated and comprehensive solutions for asset management in 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. But 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 to 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 also potential developments towards Digital Twin (DT)-enabled asset management in O&M phase. DT refers to an integrated multifaceted and multi scale digital replica of physical assets, processes and systems (Kang and Hong 2015). In the context of Digital Built Britain, a digital twin is 'a realistic digital representation of assets, processes or systems in the built or natural environment' (Róka-Madarász et al. 2016). From the perspective of information richness (as shown in Fig.1) and analytical capability, the concept of DT is broader than BIM. In this sense, DT is not only 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. Besides, 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 O&M phases, including FM management and O&M management that commonly appear in publications and standards, in the building/infrastructure level (as shown in Fig.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 O&M phase.

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 3 academic databases (Scopus, Science Direct & Web of Science) chosen for their comprehensive coverage on engineering and computation in construction, and cover a large number of journal & conference publications. And the search was restricted to the application of BIM for asset management in O&M/facility management. 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 O&M phases 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 (Volk et al. 2014, Alvarez-Romero 2014).

The effectiveness of asset management in 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, Parn et al. 2017, Lu et al. 2018). Obviously, BIM would aid in overcoming some of the complex problems in O&M phase (Sabol 2008, Love et al. 2015). 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 operation and maintenance. Targets and benefits of current BIM-enabled asset management during O&M can be summarized as follows.

- Accurate and efficient support for decision-making, monitoring and communication;
- Easy retrieval and storage of maintenance, inventory, warranty, installation and operation data;
- Enhance collaboration and increase 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;
- Facilitate 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 due to a lack of awareness of the potential benefits that smart assets (e.g., BIM) to O&M phases (Lu et al. 2018, Codinhoto and Kiviniemi 2014), a lack of demonstrators in real world of BIM-enabled asset management implementations (Becerik-Gerber et al. 2011), and a lack of a well-organised framework to design customised asset management in O&M phases.

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, are 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 optimizing the operation and maintenance management. However, the realization of case-based reasoning modules is only applicable to certain scenarios, due to the over-simplify of mechanisms. Thus, improvement in the reliability and generalization of technology and integration of information is an indispensable step towards smart BIM-enabled asset management for operation and

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maintenance. Moreover, enhancing collaboration and interoperability from organisational views is also crucial 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 produce by standardisation organisations and regulatory bodies, in the domains of BIM and asset management. As seen from last section, the challenge to implement BIM within asset management is multifaceted and 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 notability the exchange of information from design and construction phase into O&M phase.

There is an array of standards that focus on BIM and information management processes within an asset life cycle, the most comprehensive standards have been developed by BSI and ISO. Figure 3 highlights the key standards and specifications as per there associated lifecycle. The bulk of the standards focus on the design and construction phase. A few standards that are associated with O&M phase focus on the exchange of information and geometry from design and construction into O&M phase 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 easily stages within the design phase to capture their requirements.

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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 system is the ability to diffuse the traditional organisational siloed effect, as an 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 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 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

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management.

Table 2 summaries the key documentation related to asset management. The scope of asset management is board as it encompasses an assets whole-life and its value within an organisation 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. Firstly, they fail to incorporate the emerging BIM processes, limiting the use of BIM within O&M phase of an asset. Secondly, not an efficient amount of focus is given to the information management processes 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 lifecycle of an asset are supported by an array of standards that have been developed by multiple country standards and regulations organisations. Most notability the BSI has developed a comprehensive array of BIM related standards focusing on individual lifecycle phases, including design, construction and operational. 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

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processes. While BIM has been widely adopted within the design and construction phase, its adoption within the operation and maintenance phase is limited. This is partly due to the multifaced complex challenges of asset management and the alignment of the asset management frame to the BIM information management processes.

Table 2 summaries the key specifications and standards for BIM and their associated lifecycle phase. As it can be seen, the scope of BIM is board and encompasses the information management processes of an asset whole-life with many stakeholders. While the standards provide the theory and concept of BIM, several limitations are summarised in this paper. Firstly, the concept is well described, but there is no methodology provided for implementation. Secondly, due to the broadness of BIM, the standards and specifications often lack technical detail. Finally, PAS 1192-3 BIM for O&M phase fails to address the multifaceted challenges within adopting BIM for 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, BSI 2014). Furthermore, they lack support to allow a holistic organisational adoption of BIM, especially in O&M phases. This is partly due to that the standard fails to clearly address stakeholder requirements within BIM domain, simplify the exchange from design/construction into O&M phase and lack of understanding how information is used within 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 nongeometric information among different

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stakeholders in O&M phases, 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 opensource 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. IFC's overall goal is to support the exchange of information within an open source standard throughout an assets whole-life, and this broad goal makes it an extensible information model (Shalabi and Tuekan 2016).

Furthermore, Cobie is the UK government's chosen information exchange schema for BIM related information, alongside the BIM 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 (MVD). While Cobie provides a simple and user-friendly approach (via spreadsheets) to the exchange of information throughout many stakeholders within an asset's lifecycle, it is limited in proving a central validation process and risks information being lost within multiple spreadsheets, in comparison to 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 O&M phases are needed (Motamedi et al. 2014, Hamledari et al. 2017).

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 (PAS 1192-3 / ISO 55000-1/2).

Furthermore, the standards have often been developed for individual lifecycles and disciplines, resulting in limited usage throughout the whole-life cycles, as can be whiteness 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 organisation context of asset owners. While ISO 55000 supports the development of management processes within asset management, it doesn’t align to information management processes such as PAS 1192-3 or ISO 12006-2, therefore creates a disconnection from the organisational context and information management processes for their built environment assets.

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

Many orga*nis*ations and researchers have made significant efforts to accelerate the development of BIM-enabled asset management in 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 (Lu et al. 2018, Volk et al. 2014, Motamedi et al. 2014, Ding et al. 2009). Based the above analysis, corresponding limitations and gaps are still needed to put forward from these four perspectives. The following Table 3 provides a comprehensive summary of limitations and gaps in current research and standards for achieving smart asset management in O&M phases.

5. A framework for enhanced DT-enabled asset management in operation 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, comparing with BIM, DT is more suitable for complex and comprehensive data management considering the limitations of BIM listed above. Because DTs are built on data and have the capacities of integrating various data resources.

The development of ‘Digital Built Britain’ (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 UK National Infrastructure Commission states that: ‘The UK needs a digital framework for data on

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infrastructure to harness the benefits from sharing better quality information about its infrastructure; how it is used, maintained and planned'. Hence, the digital twin (DT) is widely promoted. DT is a digital model, which is a dynamic representation of an asset and mimics its real-world behaviours. DT is built on data. However, in DTs' research, a clear-defined and well-organised framework is still needed to supervise their current implementations, identify the gaps and provide roadmaps for future development. Moreover, without such a framework, they are susceptible to omit some possible improvement and key limitations.

Through a comprehensive literature review, we propose a framework for DT-enabled asset management in 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, knowledge-led methods). Efficiency means the ability to manage assets in O&M phase using effective ways with fewer resources required (e.g., time, cost, FM professionals, computational cost). Integration addresses that all assets (including data, technology, models etc.) can be compatible, integrated and further collaborate. Interoperability describes how DT-enabled asset management can be coherently dealt with various activities and seamlessly cooperated with other systems/people.

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

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5.1 Smart asset layer

The term 'smart asset' refers to conducting asset management activities with high performance, such as digital techniques, as-is BIM and information and communication technology (ICT), and further has capacities cooperated 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., RFID), distributed sensor systems, wireless communication, and mobile access (e.g., wi-fi environment) are all available in 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 O&M phase.

5.2 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 via a predefined framework and wireless technologies. Its framework is realized 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 also supports extensible innovative applications. This layer also can connect assets (including involved people) into interactive and intelligent entirety.

5.3 DT-enabled asset management layer

Successful development of DT-enabled asset management can be achieved from the following four aspects: 1) a clear and well-defined framework for DT-enabled asset management, namely the perspective framework; 2) an intelligent and seamless plan of integrating all assets during management processes, namely smart assets and smart asset integration layer; 3) a practical interoperability method for exchanging and storing information between DT and various FM systems/people, namely the digital twin and AI-supported decision-making systems. Digital twin 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 digital twin 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, status etc. 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. Finally, 4) An effective and efficient communication, cooperation and management system for users and FM professionals. For instance, site workers are required to be properly trained to understand the technologies and use the tools developed.

In general, this perspective framework is developed to depict the meaning of DT-enabled

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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 O&M phases.

6. Conclusions

With the extensive attention to implementations of smart asset management in O&M phase and the expectations to take all the advantages of BIM and digital techniques in asset management, this paper provided 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 O&M phase, this study gives an overview of academic publications related to BIM-enabled asset management and associated industry standards by summarizing various works in different areas and provides possibilities to achieve the goal of transforming to DT-enabled asset management. Detailed limitations and knowledge gaps have been 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, the DT and AI-supported decision-making systems would highly improve the intelligence and integration of the whole system. From the standard aspects, the effective and efficient communication, cooperation and management mode would be a close linkage between people and processes.

Future works are however needed to 1) Based on the perspective framework, further the detailed concepts and a case study in real practice of DT-enabled asset management will be

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developed; 2) The DT-enabled asset management at building/infrastructure will be extended to city level development; 3) Research should be conducted to investigate the alignment of the pro-posed framework with the emerging domain of smart cities, specify aligning smart assets with smart cities; 4) The interaction and impact of a smart asset with the diverse stakeholders (including customers and the general public) need to be better understood.

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

Author/year	Data sources	Algorithms	Key contribution
Shen et al. (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 lifecycle information integration
Dibley et al. (2012)	Sensor, IFC	Ontology development including sensor and building ontology	Presenting an intelligent multi-agent software framework (OntoFM) supporting real time building monitoring
Lee et al. (2013)	Sensor, BIM, GIS, Ubiquitous Sensor Network, Urban Object Identification	Integration of facilities-related information and integration of management functions	Presenting intelligent urban facilities management for real-time emergency response
Ko et al. (2013)	RFID, Web-based system, Database	Four-layer fuzzy neural network model, scheduling theory	Developing a web-based RFID FM system for enhancing facility management efficiency
Lin et al. (2013, 2014)	Mobile, Barcode, Database, BIM	An information centre for data querying	Proposing a mobile automated BIM-based facility management (BIMFM) system for FM staff in the O&M phase
Motamedi et al. (2015)	CMMS, COBIE, IFC, BIM	Data integration via connecting unique ID; 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 (BG-ETL) architecture	Proposing a software architecture for the effective integration of BIM into a GIS-based FM system
Róka-Madarász et al. (2016)	CAFM, CAD, Database	Top-down object hierarchy; Geometric Description Language	Elaborating a methodology to gathering building O&M costs data

Shalabi et al. (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 et al. (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
Arslan et al. (2017)	BIM, Sensor	Hadoop; Distributed storage	Develop a proactive safety facility management system
Suprabhas et al. (2017)	BIM, Sensor, COBIE	Data integration and visualisation	Developing an application that integrates sensor data and reports the data via the virtual model of the building.
Hu et al. (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 (MEP) management system
Chen et al. (2018)	BIM, IFC, Facility management systems	A* 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

Note 1: GIS: geographic information system; RFID: radio frequency identification devices; BEMS: building energy management systems; Hadoop: Highly Archived Distributed Object-Oriented Programming

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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 - Overview, Principles and Terminology	An overview of an asset management system with key principles and terminology	ISO 55001 ISO 55002	ISO 2014a
	ISO 55001 - management system - Requirements	Defines the requirements for the development of an asset management system	ISO 55000 ISO 55002	ISO 2014b
	ISO 55002 - Management systems - Guidelines for the application of ISO 55001	Provides guidance on management processes for meeting the requirements outlined in ISO 55001	ISO 55000 ISO 55001	ISO 2018
	Asset Management - An Anatomy (IAM)	A coherence industry guidance to asset management within 39 subject areas within 6 categories	-	IAM 2015
	The Asset Management Landscape	A framework to enable knowledge and information compared, analysed and aligned around a common understanding of the discipline of asset management	ISO 5500-1/2	IAM 2014
	Briefing for design and construction - Part 1and Part 2	Provides recommendation for briefing the operational requirements during the design and construction phase.	ISO 55000-1/2 PAS 1192-2/3	BSI 2015, 2016a
	Construction prequalification questionnaires	Provides a common set of questions to be asked of the supply chain to validate they can meet the	ISO 55000-1/2 PAS 1192-3	BSI 2013a

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		operational requirements		
BIM Related Standards	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
	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
	Specification for information management for the operational phase of assets using BIM	Focus on the operational and maintenance phase on an asset, introducing the concept of an Asset Information Model (AIM)	ISO 55000-1/2/ BS 1192-4	BSI 2014a
	Specification for security-minded BIM, 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
	Government Soft Landing (GSL)	Defines a framework for the delivery of information thought the lifecycle 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	Collaborative production of information Part 4: 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 assets whole-life	PAS 1192-3 ISO 16739	BSI 2014b
	Industry Foundation Classes (IFC) for data sharing in the construction and	Open source and vendor neutral exchange format for the example of BIM related geometry and	ISO 29481 ISO 12006-3	ISO 2013

BIM Aspects	facility management industries	information.		
	Building Information Modelling - 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 2016a
	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 2016b
	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
	Automatic resource discovery for the Internet of Things – Specification	Design of a service for IoT, in practical designed for application with broad ecosystems such as smart cities	BS 1192-4 ISO 16739	BSI 2016b

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

Technology related issues	• Lacking a well-organised demonstrator and guideline for technology selection, design and integration; • Lacking integrating BIM with various CAFM systems; • Lacking integrating BIM with other systems; e.g., 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	• Lacking a predefined strategy of transforming different information; e.g., natural languages, expert experience, digital data etc.; • 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 LODs requirements for BIM in O&M phases; • Lacking specific information requirements according to the organizational roles; • Lacking knowledge for specifying requirements of asset management early in the design phases;
Organisation related issues	• 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 O&M phases; • Lacking updated working and services workflows for smart BIM-enabled asset management in O&M phases; • Querying and updating routines are usually manual and time-consuming; • The BIM and systems are not fully integrated with the asset management workflows;

Standard related issues	• 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 lifecycle stages and disciplines, resulting in inconcinnity throughout the assets 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 the strategic documentation that does not align to process or technical requirements.

Note 1: LODs: Level of details

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Figure 1. Classifications of BIM and DT

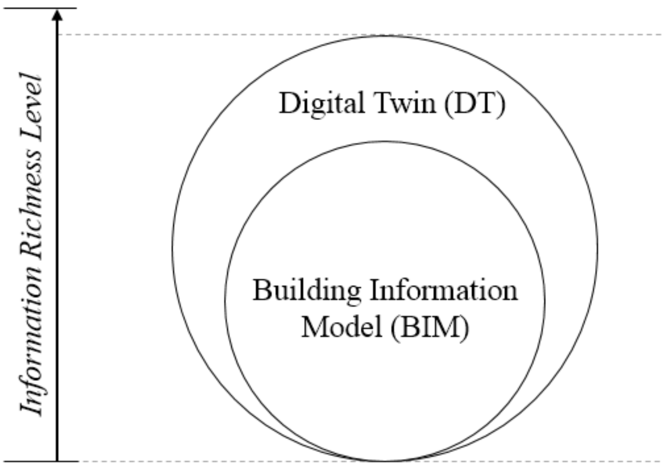

Figure 2. The research scope of this study

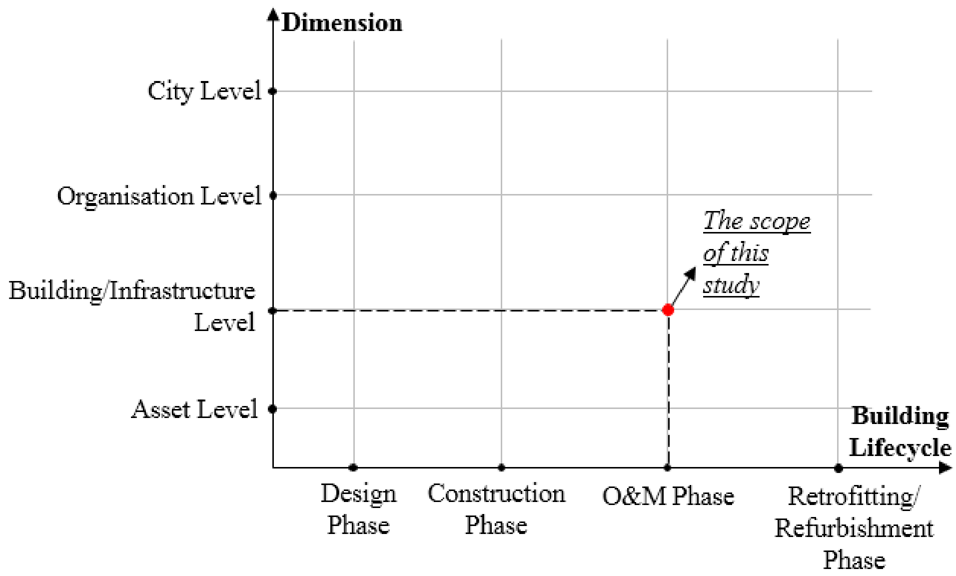

Figure 3. Summary of standards throughout an asset whole-life

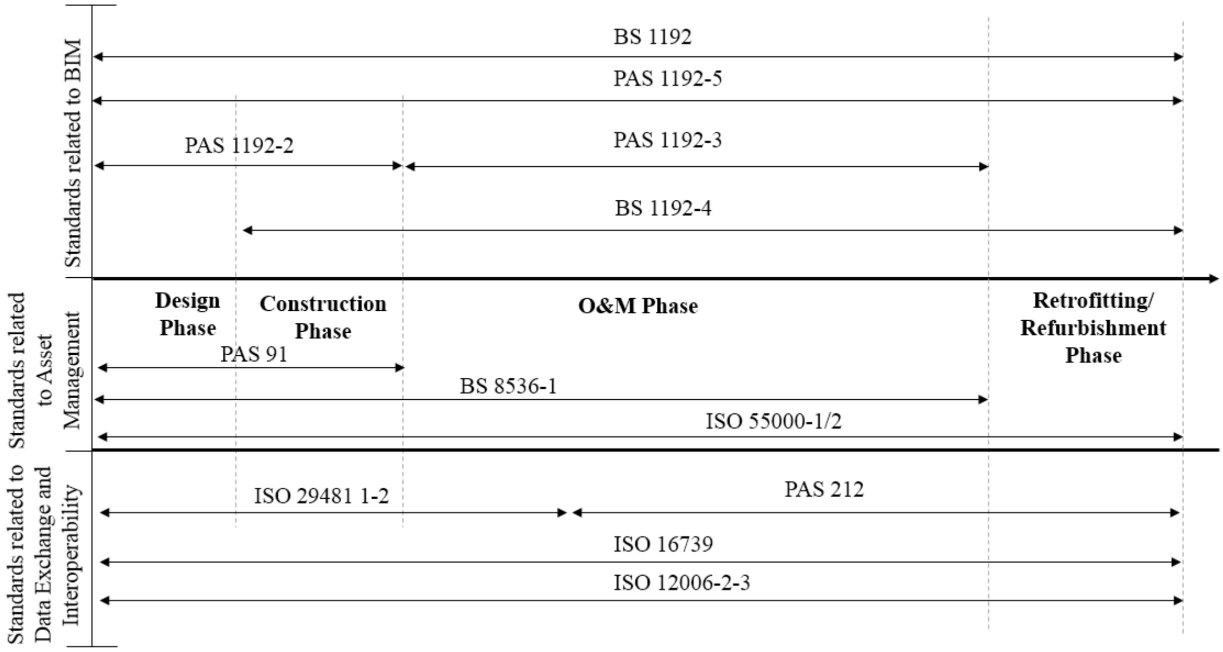

Figure 4. The potential framework of the DT-enabled asset management in O&M phases