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BIM enabler for facilities management: a review of 33 cases

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ABSTRACT

The purpose of this paper is to investigate the application of building information modelling (BIM) for asset management. It will discuss what tools and processors are used for applying BIM for asset management in construction projects. The method comprises a literature review of 33 projects that have applied BIM or planned to apply BIM for asset management functions. The findings show that a combination of software, hardware, processors, and standards can enable the BIM models to be integrated with the asset management systems. It facilitates easy extraction of information, avoid errors and duplication of work. The most popular way of developing a BIM-based asset management system is incorporating BIM asset data with CMMS or CAFM systems used for asset lifecycle and maintenance management. Engagement of stakeholders related to the operation phase is required as early as possible. Consideration should be given for protecting the information generated within the cyber environment. The research shows how BIM related tools and processors could be integrated to successfully implement BIM enabled asset management. The knowledge can be potentially useful for planning or implementing BIM enabled asset management systems. The research provides insight on the application of BIM for asset management in construction projects globally.

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Building Information Modelling (BIM); asset management; BIM enablers

Introduction

BIM provides a common platform to create and manage the representation of absolutely every feature of a construction project digitally; from the inception, design, and construction phases to the operation phase (Succa 2009; Ragab and Marzouk 2021). BIM enables the visualisation of the end product in a simulating environment which helps to pinpoint potential issues and risks (Azhar 2011; Zomer et al. 2021). Therefore, BIM could provide great benefits to every stakeholder engaged in the construction sector (Ahankoob et al. 2022; Khanzadi et al. 2020; Sacks and Pikas 2021; Zomer et al. 2021). Even though BIM is successfully applied in the inception, design and construction stages of a project (Azhar et al. 2011; Abdirad and Dossick 2016), its application in operations and maintenance (O&M) or asset management is limited (Kassem et al. 2015; Cao et al. 2022).

At the close out of the construction project, owners receive project related documents such as drawings, specifications, catalogues, O&M manuals, and warranties along with the hand-over package (Quiroz et al. 2016; Sarkar et al. 2022). However, these data come in various formats such as hard copies, and digital files and handed over by different parties and sources (Quiroz et al. 2016). During this process, the information needs by the owners, the facilities management team or other part of the organisation could sometimes be lost or not accessible. These issues can be effectively addressed by using a BIM platform for the O&M of a construction project (Munir, Kiviniemi, and Jones 2022).

According to Kassem et al. (2015), BIM value in the O&M stems from improving the data related to assets and Facilities Management (FM) processes in terms of digitalising the physical information handover process, enhancing the asset data accuracy, assuring equal accessibility to asset and FM data, increasing the efficiency of work order performance and support facilities field tasks. Therefore, BIM can deliver a common storehouse for all data and information related to the asset management project, enabling the planning and tracking of maintenance works, tracing the changes and the history of an asset and information accessibility across the whole organization. (Quiroz et al. 2016). However, identifying the right tools and processes is necessary to facilitate the realisation of and maximise the advantages of implementing BIM to the project's O&M stage. Sanchez et al. (2016), has defined such tools and processors as '**BIM Benefits Enablers**'. There are 32 BIM benefits enablers as shown in Figure 1 below:

The current research on BIM for O&M has mostly focused on energy management and still in its initial stages (Mohammed 2022). Furthermore, most research on the application of BIM for asset management or FM have examined the advantages and challenges of BIM (Pärn et al. 2017; Hull and Ewart 2020). However, the effective adoption and execution of BIM requires a detailed analysis of various enablers. According to a survey done by the Liverpool John Moores University and the Zurich University of Applied Sciences and BIFM, 72% of the respondents agreed that the FM industry has no clear understanding about BIM and 91.3%

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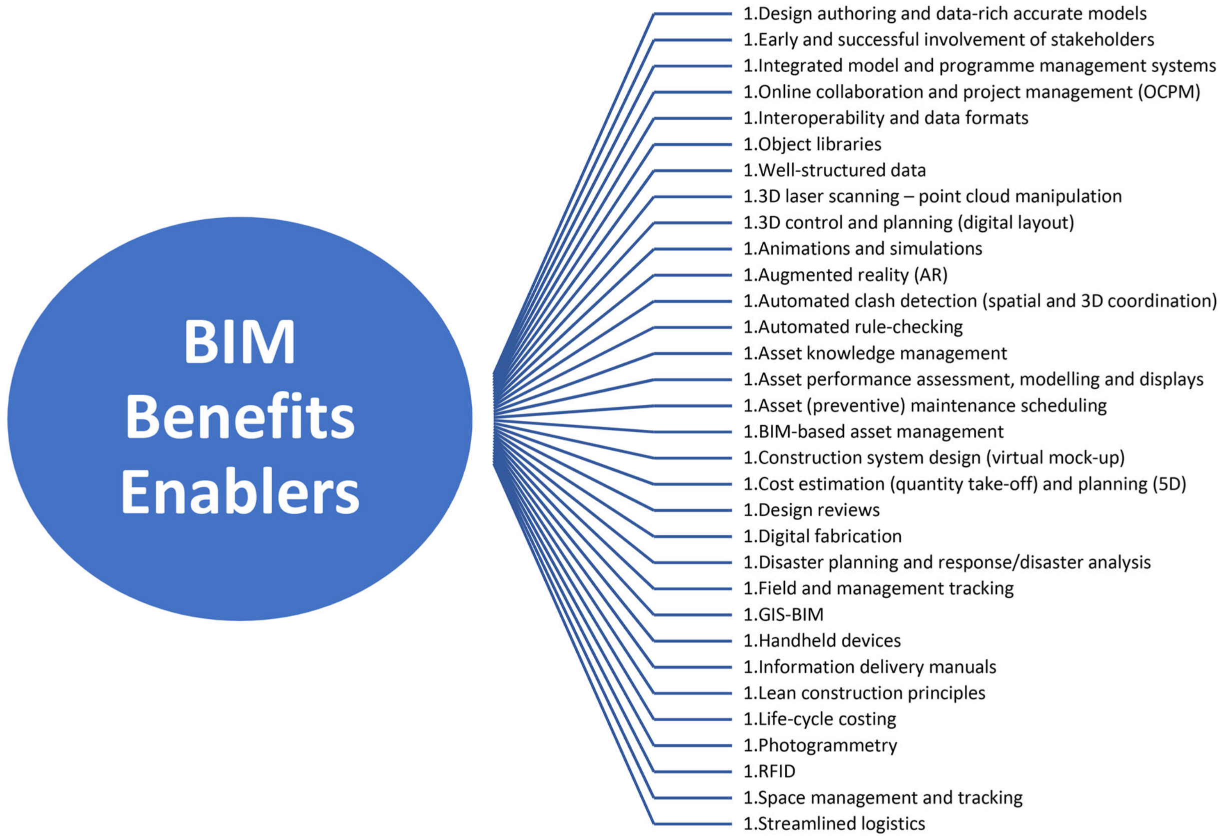

Figure 1. BIM benefit enablers.

have agreed that proper adoption of BIM would benefit FM professionals to gain effective results in the management process (Ashworth and Mathew, 2017). According to Ashworth and Mathew (2017), there should be a strategic approach to BIM-based asset management, as assets often remain the second biggest cost for an organisation after human resource. Therefore, this study explores the application of BIM in asset management in infrastructure projects, healthcare projects and other major educational and commercial projects and elaborate the BIM enablers required for successful implantation of BIM for asset management.

Research method and process

The investigation was carried *via* a literature review to gain comprehension on the application of BIM in asset management. Journal articles, conference papers, books, government and institutions websites, and reports were reviewed to collect relevant literature. 33 projects which have applied BIM in various ways for asset management functions were identified. Figure 2 shows the identified 33 projects. The 33 projects reviewed can be further categorized according to their function such as infrastructure (11), airports (05), educational (04), healthcare (07), an iconic building (01), public building (01) and commercial (04) as shown in Figure 3. The reviewed projects have applied BIM or planned to apply BIM for asset management functions. The selected projects were analysed using the BIM benefit enablers identified above. The next section discusses the findings of the analysis.

BIM enablers in the case projects

As mentioned above, this paper was to investigate the application of BIM in asset management in infrastructure projects, healthcare projects and other major educational and commercial projects. The key enablers related to BIM deployment management in relation to asset management were identified and discussed in this section.

Design authoring and data-rich accurate models

BIM facilitates designing and information management by using design authoring tools to generate 3D models and audit and analysis tools to explore and/or feed the information pool (Le et al. 2022). The first step of implementing BIM is identifying the design authoring tools and linking the 3D model with database of assets, amounts, methods and techniques, expenses, and schedules (Penn State College of Engineering, 2019). Supplementary Appendix 1 describes the tools used in the projects considered.

Early and effective stakeholder engagement

Early engagement of stakeholders enables to identify what tools/software are used and the information requirement throughout the project lifecycle. Therefore, the information can be built into the 3D model from the beginning. Most projects have highlighted that they have engaged all disciplines (civil, infrastructure, design, construction) in the design and construction phase (Sanchez et al. 2014; Autodesk 2016; Rafael, et al. 2018; Tylor 2018) and the FM team is engaged once the construction was completed. The Prince Mohammad Bin Abdulaziz International Airport project emphasized the importance of engaging the FM team during design phase of the project. As a result of engaging FM team to finalize the labeling and feature requirements throughout the construction, several changes and modelling duplications were made in room and tagging classification which have otherwise required extra costs and

Figure 2. Identified projects.

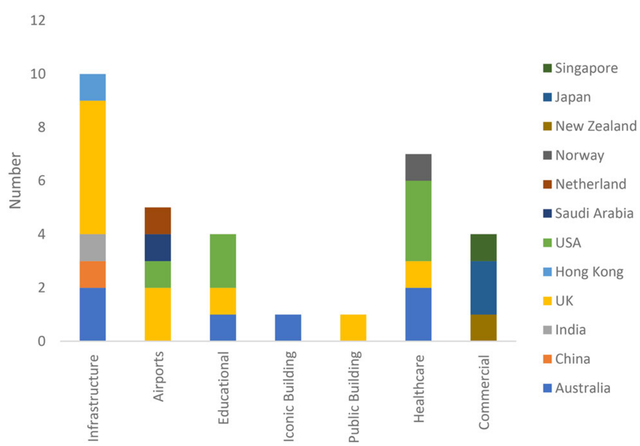

Figure 3. Classification of the projects based on the countries.

time (Rafael, et al. 2018). However, projects for example, Howard Hughes Medical Institute, IBM Japan - Osaka Building, Schiphol Airport have engaged the FM team early in the process which enabled carefully planning and executing the whole process, establishing strong communications and building trust among team members (Rafael, et al. 2018, Wood 2011). Those projects such as Standford Neuroscience Health Center which have only considered BIM at the operational phase have involved Facility maintenance staff, operation staff from engineering, asset management, resource management, infection control, PMO, E&M, EH&S and construction, asset management software vendor, BIM software vendor with the BIM-FM application process (Rafael, et al. 2018).

Integrated model and programme management systems

In contrast to a Federated Model, an integrated model such as Design Models (DModels), Construction Models (CModels), Operation Models (OModels) or a full Project Lifecycle Models (DCOModels) combines every aspect of separate models into a common database (BIM Dictionary 2019). A cloud-based 3D BIM based solution with the mobile/iPad inspection app which ensures the data entered is automatically synced with the 3D model is commonly considered. For example, Wynyard Quarter Innovation Precinct used Tableau (BIMINNZ 2016; BECA; 2016) and Maharashtra Metro Rail used SAP (Rib Software 2018). In the operations stage, Prince Mohammad Bin Abdulaziz International Airport, linked the construction and asset documents with the element groups in the BIM-FM platform and the BIM asset data was used to fill the CMMS database (Rafael, et al. 2018). Authoring requirements, management of the BIM model, periodic software update requirements, long-term accessibility of the BIM models were defined in the BIM execution. In the A556 project, data was captured from site using mobile technology and uploaded to the Cloud platform. The initial digital format of information is first converted into IFC and then into COBIE to create asset information model (AIM) (Autodesk, 2015).

Online collaboration and project management (OCPM)

The cloud-based 3D BIM solutions enable real-time secure collaboration and data management across the project lifecycle and with multiple stakeholders (Sarkar et al. 2022). For design and construction phase, Autodesk BIM 360 Team has been used. (e.g.: Denver Airport) (Wysocky 2014; Davie 2019). Bentley ProjectWise is another tool which is used for collaboration and document management, store all project information and sharing of project information (e.g.: The A556 project) (Aziz et al. 2014; Autodesk, 2015). In asset management context, all information on assets and the related documents resides on the BIM-FM system. The CMMS/CAFM databases are occupied and coordinated with the BIM-FM platform. The work orders can be accessed and stored within the CMMS/CAFM database. Workorders can be opened and searched by the FM team using the system or through mobile applications or through WIFI network. This approach has been considered in Denver airport (Wysocky 2014; Davie 2019).

Interoperability and data formats

Accurate, reliable, and consistent data exchange is crucial for proper project collaboration. .ifc open file format and other openBIM data formats, including Construction Operations Building Information Exchange (COBie) for BIM data, gbXML, LandXML supports the interoperability of the BIM model within different platforms (Sonda 2016). Supplementary Appendix 2 shows the data formats of several projects that have considered for the BIM models.

Object libraries

A BIM object is any aspect of a building that is not part of its structural characteristics. There are two types of BIM objects: 1. Component objects which have fixed geometric shapes such as windows, doors, boilers, piping, air ducts, electrical work, etc.; 2. Layered objects which do not have fixed shapes or sizes such as carpets, roofing, walls and ceilings. For example, in Prince Mohammad Bin Abdulaziz International Airport, BIM-FM library development was based on eleven BIM models for each discipline and floor levels; the Howard Hughes Medical Institute highlighted that object libraries were developed based on the systems across the facility and in Standford Neuroscience Health Center project, a data directory was developed for the main features and information needed for the Standford team (Rafael, et al. 2018).

Well-structured data

Common Data Environment (CDE) is the key to well-structured data. As per project London Crossrail, The British standard PAS 1192 provides a complete overview of the CDE and it is adopted to enhance interoperability using BIM (Tylor 2018; Crossrail 2019). For example, the new Royal Adelaide Hospital (nRAH) project has used the federated model, at LOD500 level, and has been delivered to the FM provider and the state for asset management (Mills 2016). Heathrow Airport project have Level 2 implementation criteria for HML data structure/Maximo data structure (Verma 2013). Also, IFC and COBie specifications are used to maintain the structure of the data in projects such as Pyrmont Bridge, Denver Airport, Sydney Opera House, Gatwick Airport, IBM Japan, TAKENAKA - NTT Building, Schiphol Airport (Wysocky 2014; Davie 2019; Wood 2011; Zuuse, 2019; Sahlman 2015; Sanchez et al. 2015). Therefore, with BIM the facility's as-built data can be accessed from a central, reliable platform. In projects such as Prince Mohammad Bin Abdulaziz International Airport, the BIM-FM platform provides a higher granularity of information (as BIM data was structured in 11 BIM models according to the discipline and floor level) in comparison to the CMMS database which manually extracted data from hardcopies or site survey (Rafael, et al. 2018).

3D laser scanning – point cloud manipulation

Laser scanning and point clouds accurately capture the real-world circumstances of the project into a 3D scan. The scanned data is fed into a 3D modelling platform to generate as-built models or to update the design as per the practical conditions (Dekker 2019). LiDAR scanning is the most popular method which has been used in Pyrmont Bridge, Denver Airport, London's M25 Motorway, Lower Catskill Aqueduct, Schiphol Airport and Victoria station London Underground (upgrade) (Wysocky 2014; Davie 2019; Rafael, et al. 2018; Zuuse, 2019; Sahlman 2015; Desai 2012; Weide, 2017; Esri 2018). In Lower Catskill Aqueduct, LiDAR scanning is used to collect the information of the aqueduct. The current conditions and original contract documentation are imported into ArcGIS Online to manage all known assets and locate several unspecified assets, such as the access points to manholes that have been obscured by foliage for engineering evaluations (Esri 2018). According to London's M25 Motorway project, laser scanning methods are introduced to improve the safety of the workers and reduce cost, program, and CO_2 emissions (Desai 2012).

3D control and planning (digital layout)

BIM-enabled 3D control and planning is used to layout the services, assemblies or automatically control the movement and location of the equipment (T & T Design, 2019). For an example, it can be easily determined whether the exact depth of excavation is attained by creating a wall layout using a total station with pre-loaded points and/or GPS coordinates (Penn State College of Engineering, 2019). Naviswork, Autodesk's BIM 360 Glue, Ecodomus visualization, iFaME desktop application and Hologram are the software and tools used by the examined projects for 3D control and planning.

Animations and simulations

Apart from 3D visualisation, the BIM model can be animated and use for simulation and analysis (Khanzadi et al. 2020). For example, the Project A556 used Civil 3D and 3DS Max to develop a fly through animated view of the new route using Civil View extension and demonstrated it in their public consultation events (Rosario 2016). Further, in Victoria station London underground (upgrade,) all communications during the construction phase were done using 3D and animated PDFs obtained from the project information and 3D models (Rafael, et al. 2018). In Perth Children's Hospital, animations were used to present information to clients (Sanchez et al. 2014). Avatars were used in the model to assist the clients to understand how the design or layout would be functioned in the actual context. Also, the client and end-users virtually walked through the design to effectively communicate with the design team prior to any decision-making.

Another interesting fact highlighted in Østfold Sykehus healthcare project in Norway is combining BIM with the virtual gaming technology. Østfold Sykehus opted to use BIM in design, construction, and operation. It delivered a comprehensive simulated model in the design phase which acted as the digital prototype of the proposed building (Merschbrock et al. 2014). In order to expand the use of digital modelling data, a game using the BIM data was created. Game technology could be used for staff training purposes during the operations phase.

Augmented reality (AR)

AR combines the real environment with virtual information and delivers it in real-time with the use of advanced camera, sensor technology and BIM models. For example, London Crossrail had trial for a Bechtel-developed AR mobile (iPad) application to verify if it could increase the process and quality efficiencies of the prevailing site endeavors (Smith 2017). According to London Cross rail experience, AR had the potential to benefit through capturing construction progress information against an AR 3D model of the construction site and automatically convert it into a 4D model to support the project planning process (Smith 2017). Mapletree business city II project has used Autodesk A360 panoramic rendering and google Cardboard. Google Cardboard presents the rendered BIM model when scan the QR codes given by the A360 cloud software (Rafael, et al. 2018).

However, none of the projects have considered using AR for asset management purposes.

Automated clash detection (spatial and 3D coordination)

Automated clash detection provides a computerized indication of conflicts and discrepancies of the design, whether it is structural or MEP (33D mech designs 2018; Akhmetzhanova et al. 2022). Clash detection helps reduce project errors. Autodesk Navisworks in combination with Autodesk Revit, AutoCAD Civil 3D, Subassembly Composer is highly used for this process (e.g.: Denver Airport, The A556 project, London's M25 Motorway, New York-Presbyterian Healthcare (Manning and Messner 2008; Wysocky 2014; Autodesk, 2015; Davie 2019).

Automated rule-checking

Currently, automated rule-checking is carried out in the design-review phase however it is not restricted only to the design-review phase. For example, Pyrmont Bridge, Sydney have used Solibri Model Checker for compliance with codes and planning restrictions (Zuuse, 2019; Sahlman 2015). Perth Children's Hospital and Denver Airport used Autodesk's BIM 360 to prevent having contrasting systems and conduct quick audits during various phases of construction (Wysocky 2014; Sanchez et al. 2014). Also, Mapletree business city II has used personalized Revit families with parametric code checking elements to check compliance with regulatory requirement (Rafael, et al. 2018).

Asset knowledge management

ISO 55000 definition of asset management is the synchronized actions of an organisation to achieve value from assets (Yates 2018). Assets include plant, machinery, property, buildings, and other items which have a specific value to the organization. BIM enables developing structural, electrical and mechanical components to a 3D model. Therefore, all asset details and related documents reside in the BIM model can be assimilated with the BIM-FM platform. For example, Pyrmont Bridge, have integrated the structural components, electrical and mechanical components of the bridge to a 3D BIM model which is accessed *via* a cloud-based 3D BIM software for the periodic inspection associated with preventive maintenance of the assets (Zuuse, 2019; Sahlman 2015). The following projects have also used BIM for asset knowledge management:

- Prince Mohammad Bin Abdulaziz International Airport: BIM models in IFC format are imported and linked to the BIM-FM platform. The CMMS database is occupied and coordinated with the BIM-FM platform (Rafael, et al., 2018).
- Howard Hughes Medical Institute: FM-enabled BIM includes the Revit model, the last mile databases (CMMS, BAS) and visualization/analysis middleware (Rafael, et al., 2018).
- Denver Airport: Revit model, SQL Databases and Maximo database for asset knowledge management (Wysocky 2014; Davie 2019).
- Maharashtra Metro Rail: Asset Information Management System has developed a digital backup and a labelling system from design stage for eliminating information loss over the project's life cycle (Rib Software 2018). Further, they have a 5D BIM system which provides a mutual environment for 3D models and the associated data called Electronic Data Management System (EDMS) (DQ India Online 2018, Raval, 2018; Excelize, 2019). The 5D BIM digital project management provides graphical representation of vendor contracts and asset warranties along with proper warnings (Rib Software 2018; DQ India Online 2018).
- Wynyard Quarter Innovation Precinct: document integration such as contract documents and O&M manuals into appropriate assets in the BIM model (BIMINNZ 2016).

Asset performance assessment, modelling and displays

Several methods have been used for Asset performance assessment, modelling and displays:

- Pyrmont Bridge used a cloud-based 3D BIM software to develop the condition assessment requests for the inspected elements. The bridge inspectors can input the information automatically, make comparisons with the former year's details and synchronise the photos automatically with the data in the 3D model (Zuuse, 2019; Sahlman 2015).
- Standford Neuroscience Health Center uses Ecodomus to provide 3D visualisation of the facility for FM that connect BIM and real-time facility operations data acquired from the Building management system and FM software (Rafael, et al., 2018).
- Wuhan Metro used equipment monitoring with BAS integration which have the options for cloud-enabled video monitoring of stations and the neighbourhood, air quality monitoring, space Inventory and performance (ARCHIBUS, 2016; Zhang et al. 2016).
- Sydney Opera House has a building condition FaPI SQL database with weekly/quarterly updates on the rating of the building presentation (Cooperative Research Centre for Construction Innovation 2007); Sanchez et al., 2015).
- Mapletree business city IIuploaded the as-built BIM model to the iPad enabling the FM to discover the location of hidden services (Rafael, et al., 2018).

Asset (preventive) maintenance scheduling

In most projects, preventive maintenance scheduling is done through the Computerized Maintenance Management System (CMMS) or the Computer-aided Facility Management (CAFM) system. IBM Maximo, SAP, Agility, IFS, Tiscor, Integrated Asset Management Information System - Bentley Exor Systems based system and ARCHIBUS Web Central are some of the examples used in the projects reviewed. The above platforms are used for asset life cycle and maintenance management and provide greater efficiencies for (Verma 2013; Rafael, et al. 2018; BIMINNZ 2016):

- Asset maintenance and replacement scheduling
- OPEX and CAPEX predictions via better data availability
- Forming work order (WO)
- Assimilating energy use with the building performance
- Hazards management and disaster revival

Such platforms can also be accessed remotely by using mobile devices and iPads which helps in real time tracking and updating maintenance activities which helps management to make educated decisions and delivers data for third-party functions (Eastman et al. 2011; Chen et al. 2019; Cheng et al. 2020).

BIM-based asset management

BIM-based asset management connects the asset data recorded in BIM during building design and construction with the building operations phase. Enterprise asset management is done *via* CMMS or CAFM systems which manage the asset lifecycle and its maintenance. The most popular platform is IBM Maximo. For example, in Gatwick airport, Revit into Maximo integration enabled to create an asset register, consisting of over 2000 location related assets in less than one hour (Wood 2011). Similarly, Denver airport, Stanford Neuroscience Health Center, IBM Japan - Osaka Building TAKENAKA - NTT Building, Schiphol Airport, Heathrow Airport have integrated asset information from the BIM model to IBM Maximo (Wood 2011; Verma 2013; Wysocky 2014; Weide, 2017; Davie 2019; Rafael, et al. 2018).

Further, Prince Mohammad Bin Abdulaziz International Airport have used EcoDomus FM consisting of documents linked to assets, schemes, locations, amenities, as per the COBie rules which enables data filtering based on their locations or categories and building custom reports and the documents such as submittals, datasheets, warranty, specifications, and the like. (Rafael, et al. 2018). Maryland General Hospital (MGH), the CMMS system, Tiscor which was already being used by the client was integrated with the BIM model created through Tekla Structures (Eastman et al. 2011). London's M25 Motorway Connect Plus is working with AMSIT to develop an asset management system for one of the most complex highways in the world (Skanska 2013) and Ecodomus and BIM Academy are working with Hongkong MTR on a BIM-enabled Facilities Management project (EcoDomus 2016).

Construction system design (virtual mock-up)

Virtual mock-ups deliver a collaborative design authentication process. Perth Children's Hospital used virtual mock-up to explain CCTV cameras coverage to achieve location approval (Sanchez et al. 2014). Model navigation assisted in identifying the conflicting areas between utilities and partitions and the model animations demonstrated the construction order. Digital mock-ups were created with the use of Autodesk Revit software (Architecture, Structure and MEP), and Autodesk AutoCAD Civil 3D. For example, project Mapletree business city II used Autodesk Revit to produce a detailed mock-up of the reinforcement column for designing the complex rebar reinforcement which enabled accurate offsite fabrication of the rebar cage and seamless positioning and installation on site (Rafael, et al. 2018). Although, the use of virtual mock-ups is not considered in the asset management stage of the reviewed projects, it's useful technique that can be useful in replacement or refurbishment projects.

Cost estimation (quantity take-off) and planning (5D)

5D BIM applies expenses to the BIM model (Khanzadi et al. 2020). 5D BIM enables automatic generation of quantities that can help analyzing data and offering better guidance, and studying the ways to improve the design, proficiency, productivity, and cost (Exactal 2015). Victoria station London Underground (upgrade) considered Computer Aided Design (CAD) combined with time schedules and cost details, where quantities of materials have been calculated while exploring the impact of design changes on the cost (Rafael, et al. 2018). Also, Maharashtra Metro Rail used iTWO and SAP systems which integrates 5D BIM simulation by linking 3D model, schedule and cost (New desk 2017; Rib Software 2018; DQ India Online 2018; Raval, 2018; Excelize, 2019).

Design reviews

Design reviews allow stakeholders to assess a 3D model and provide a feedback to confirm various design features. Navisworks and BIM 360 from Autodesk are such project review software solutions (Sanchez et al. 2014; Autodesk 2019). The tools properly coordinate the documents, minimize conflict, and improve communication. Also, stakeholders without modelling skills could use and manipulate the model to get more information.

Digital fabrication

The digital fabrication process of a construction project includes computerized design methods and automated manufacturing process. For example, 3D printing has been used to create a model of the Plumbing system in Mapletree business city II (Rafael, et al. 2018). However, digital fabrication has been considered only in the design and construction phase.

Disaster planning and response/disaster analysis

BIM provides useful real-time data to plan for a natural disaster or for emergency situations. In Maharashtra Metro project, SAP was used to integrate the footage of more than 1000 cameras positioned across Nagpur and IoT algorithm was used to create triggers and warnings and deliver perceptions in case of an event (Rib Software 2018; DQ India Online 2018; Excelize, 2019). This technology is ideal for emergency response if any situation occurred. Standford Neuroscience Health Center have trialed The BIM model and the Ecodomus visualisation for Fire analysis and ICRA/PCRA reviews. However, it has not been used across the project, except to train and brief the sub-contractors about safety concerns (Rafael, et al. 2018).

Field and management tracking

BIM 360 Field is used for field and management tracking in the construction phase of the projects (e.g.: Denver Airport, (Wysocky 2014; Davie 2019). Wynyard Quarter Innovation Precinct used Tableau to create digital dashboards which can provide latest view of the data capturing percentage of BIM 360 Field (BECA 2016). During the operation phase also, several software has been considered. Pyrmont Bridge operations team tracks daily tasks of the inspectors and their progress through the Cloud-based 3D BIM software (Zuuse, 2019; Sahlman 2015). In Standford Neuroscience Health Center, Maximo is used to update the status of the field work (Rafael, et al. 2018). Maryland General Hospital uses Vela Systems software. The field personnel record and update field data such as inspection outcomes, assigning data, and the like by using the tablet PC software created by Vela Systems. Also, they can easily access the centralized database in the field by using the tablet (Eastman et al. 2011).

GIS-BIM

BIM and GIS (Geographic Information System) are two critical technologies, whose integration can improve the effectiveness of the asset management processes. The following projects have considered GIS-BIM:

- Denver Airport, GIS-BIM FME exporter was used. It is a one directional exchange. Therefore, GIS to CMMS expanded use of existing BUS integration for part 139 reporting. It was a bidirectional data exchange (Wysocky 2014; Davie 2019).
- Maharashtra Metro Rail has the location of all 500,000 assets logged in the system so that one click on the asset in SAP can locate it in a 3D map (Rib Software 2018).
- Wuhan Metro has used GIS technology to deliver satellite and 3D images, map the facilities, provide access and 360-degree photo view to drawings and room layouts to enhance the visualisation on space management (ARCHIBUS, 2016).
- The Sydney Opera House main complex is sited on a location with historic advancement, archaeological items, current and abandoned utilities, and below ground and underwater features. Therefore, GIS systems are used to obtain information and integrate data such as cadastre, land consumption, topography, utilities and asset records in IFC format (Sanchez et al., 2015).
- London Cross rail has also increased the performance by connecting documents, 3D models and the like with GIS mapping (Tylor 2018; Crossrail 2019).

Handheld devices

iPad and mobile devices are mainly used in all projects in design, construction and operations phases. These handheld devices provide 3D images of the facilities and allow accessing the management information anywhere anytime. For example, the new Royal Adelaide Hospital (nRAH) estimated that onsite use of mobile tablets for checking and reviewing data can reduce rework by 12% (Mills 2016). School of Computer Science, Engineering and Mathematics/Flinders University, South Australia has identified the use of handheld devices for capturing inspection information and performing work orders efficiently in the field on a tablet, providing efficiencies (FM Media 2016; Zuuse, 2019).

Information delivery manuals

According to Texas A&M Health Science Center, information manuals such as O&M manuals, warranties, work orders, submittals, and other records are enclosed in the CMMS to refer when needed (Rafael, et al. 2018). The A556 project created an Asset Data Management Manual (ADMM) for handover of the project (Skanska 2013). Standford Neuroscience Health Center developed a BIM-FM guideline for asset management (Rafael, et al. 2018). Wynyard Quarter Innovation Precinct uploaded necessary documents such as work orders and O&M manuals into the BIM model (BECA 2016).

Life-cycle costing

Whole-life cost indicates the total cost of possession throughout the asset's life. Standford Neuroscience Health Center, The A556 project, Maharashtra Metro Rail, and Sydney Opera House have highlighted the importance considering life cycle cost at the start of the project. For example, the asset strategy of Maharashtra Metro Rail, the asset labeling procedure and the asset management workflows were prepared considering the assets' whole life cycle (Rib Software 2018).

Photogrammetry

Photogrammetry is taking pictures and directly uploading them to the BIM model to link with the relevant elements in the model. Perth Children's Hospital have considered using of tablets to access the information and capture data quickly and easily *via* photogrammetry (Sanchez et al. 2014). Pyrmont Bridge is also using mobile devices to take photos during inspections which will be automatically synchronized with the 3D model and related data (Zuuse, 2019; Sahlman 2015).

RFID

Radio Frequency Identification (RFID) tags are used for assets tracking (Sarkar et al. 2022). For example, Prince Mohammad Bin Abdulaziz International Airport uses an Object ID system in their asset database where every equipment in the BIM model was assigned with an ID as a specific parameter so that the equipment can be sorted by location and/or system (Rafael, et al. 2018). Perth Children's Hospital use RFIDs to track asset with unique IDs. The tracking system is linked to a database to trace the progress of real objects (Sanchez et al. 2014).

In Wuhan Metro, the integration of RFID and QR Code integration is influential for effective data capturing, precise asset management and equipment tracing, recovering of maintenance files, and quickly reporting the work request *via* mobile devices (ARCHIBUS, 2016; Zhang et al. 2016). Some project use barcodes instead of RFIDs. For example, in Wynyard Quarter Innovation Precinct, barcodes are assigned on certain assets to scan their information (within Building Ops) and history using mobile devices, on request (BECA 2016). Maryland General Hospital also uses barcodes and specialized software on tablet PCs, and they have used Bartender to generate the barcodes with Code 39 Standard Barcode Symbology (Eastman et al. 2011).

Space management and tracking

BIM models can be utilized to realistically allocate, manage, and trace spaces and associated resources in a facility. The facility management team can use the BIM model to explore how a certain space is currently been used and accordingly do the necessary changes (State of Minnesota 2014). For example, to identify which part of the building to be occupied during a project's renovation. To do so, the BIM model should be integrated with a spatial tracking software:

- Standford Neuroscience Health Center use Ecodomus to view the model and obtain information of spaces (Rafael, et al., 2018).
- Sydney Opera House uses Mainpac and space planning software (Sanchez et al., 2015).
- Kuweit Ministry of Education use iFaME application which enables micro level management of assets and facilities in the school building. The facility managers could effectively allocate the space and assets, maintain, and manage the facilities while attending to other aspects of school's property management (El-Gamily and Rasheed, 2015).

Streamlined logistics

According to Pyrmont Bridge project, the 3D BIM model provides a clear understanding of the work and material requirement for maintenance or restoration activities (Zuuse, 2019). For

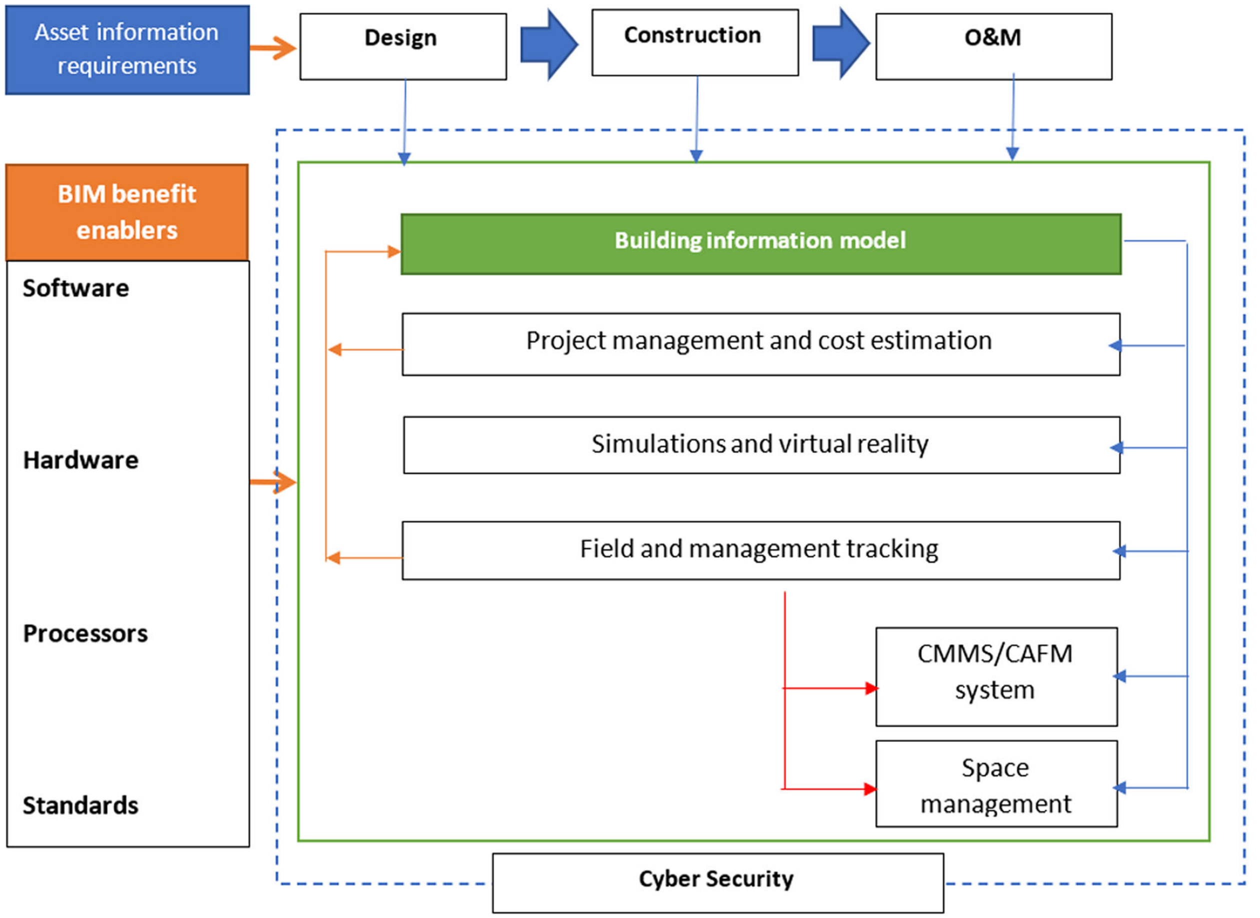

Figure 4. Application of BIM technology towards successive asset management.

example, there is the ability to say exactly the requirement of primer or paint need for maintenance and the model made it easier to define the material (Zuuse, 2019). This will provide the contractors a much better understanding on the work scope and lower the risk of involving in any project (Ahankoob et al. 2022; Zuuse, 2019; Sahlman 2015). Further, from Maharashtra Metro Rail we could learn that the inventory and spares could be properly managed by collaborating through the SAP systems which is additionally connected with the backend and the financial schemes (Rib Software 2018). Therefore, the process of integrating BIM with asset management helps to streamline the logistics and supply chain of the project (Le et al. 2022).

Discussion

Based on the above findings BIM benefit enablers can be categorized under the design, construction and operations stages of the project life cycle which are summarized in Supplementary Appendix 3. The findings show that BIM benefit enablers are mostly software and tools, but they could also be hardware, processors as well as industry standards.

Tools and processors vary based on the year that the projects were implemented. Supplementary Appendix 4 provides a summary on the application of tools in the selected cases from 2001–2018. The results show that in the projects after 2008 the application of BIM tools had dispersed across the design and construction and O&M phases. Use of LiDAR scanning, animations and GIS is popular among most projects after year 2008. Furthermore, most cases have considered use of multiple tools (e.g.: Autodesk Revit, Ecodomus, Navisworks and IBM Maximo) in combination to create an integrated asset management platform. In the most recent cases from 2015–2018 engagement of the FM team with the design and construction early in the process have been considered. Therefore, we can identify that there is a growth and use of digital technologies and practices which focus the whole life cycle of the asset that can be considered from inception stage to the disposal stage of an asset's life cycle. Based on the above findings the application of BIM technology towards successive asset management can be demonstrated as shown in Figure 4.

As shown in Figure 4, use of BIM throughout the lifecycle of the project can support Project management and cost estimation, simulations and virtual reality, field and management tracking, asset management and space management systems. BIM benefit enablers discussed above can support successful integration of BIM technology along the phases of project lifecycle. A substantial amount of asset related information is generated through this process in a collaborative cyber environment. Therefore, there is a necessity to implement cyber security measurements to safeguard the organisations and its stakeholders against related cyber security risks.

Conclusion

Currently, the use of BIM in O&M or for asset management is limited. Therefore, it is crucial to understand the industry current practice for considering the use of BIM in asset management applications. This study explored the application of BIM in asset management in local and global infrastructure projects, healthcare projects and other major educational and commercial projects. Under this study 33 projects were reviewed. The study used 32 BIM benefit enablers defined in Sanchez et al. (2016) to analyse the identified projects.

The findings revealed that the use of BIM for asset management can deliver multiple benefits to any facility or owner in any industry. One main benefit of having BIM-FM system is linking 3D model data directly with an asset database and visualisation enables the operational team to access the required information easily, avoid errors and duplication of work which results in time and cost savings. Further, with proper understanding on the operations, facility managers can forecast issues and faults rather than reacting to an actual issue. Also, operations can be simplified for years saving time and money. Faster compliance of regulation and requirement, higher customer satisfaction, improved safety and reduction of risks are several other benefits of applying BIM for asset management. The most popular way of implementing a BIM-based asset management system is integrating BIM asset data developed in building design and construction phases to asset management systems such as CMMS or CAFM systems used for asset lifecycle and maintenance management. From the reviewed projects, the most popular asset management platform for BIM integration is IBM Maximo.

However, application of a BIM-based asset management system is not an easy task. Estimating the whole life cycle during the inception phase of the project requires to know the whole picture of assets and its uses. Also, early engagement of stakeholders is required to identify what tools/software are used and the information requirement throughout the project lifecycle. Most projects have suggested that all disciplines (civil, infrastructure, design, construction) related to their design and construction phase and the FM team should be engaged at the start of the project for an effective deployment of a BIM-based asset management system. Moreover, consideration should be given for protecting the information generated within the cyber environment.

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In accordance with Taylor & Francis policy and our ethical obligation as researchers, we are reporting that we have no potential competing interest that may be affected by the research reported in this paper.

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