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Planning and developing facility management-enabled building information model (FM-enabled BIM)

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ABSTRACT

Successful implementation of FM-enabled BIM can be achieved with 1) a clear definition of what FM-enabled BIM constitutes, 2) a seamless and practical process of collecting the FM-enabled BIM data throughout project development phases, and 3) a well-executed interoperability plan for exchanging data between BIM tools and facility management systems, such as Computerized Maintenance Management System (CMMS). This research contributes to the body of knowledge by first defining, and examining one of the first few pilots implementation of FM-enabled BIM, and discussing the challenges encountered and the lessons learned, and then by proposing a research framework for future researchers to systematically and strategically build the knowledge foundation on BIM for FM field. The implementation process described and the lessons learned captured in this pilot project provide valuable insights into the successful implementation of FM-enabled BIM.

1. Introduction

As a new paradigm, Building Information Modeling (BIM) is transforming the process of developing, sharing, and capturing project information. BIM applications in design and construction have outgrown the research stage and are now widely deployed; however, application of BIM in the facility management (FM) phase is still developing, and the research in this area, while growing, is still at a very early stage. Indeed, the potential of BIM to transform the FM phase has yet to be fully exploited [1,2]. Considering that the FM phase lasts much longer than the design and construction phases, any process efficiency BIM can occasion will introduce a much greater cost savings [3]. According to a report by the National Institute of Standards and Technology (NIST), the estimated cost of inadequate interoperability in the U.S. capital facilities industry is $15.8 billion per year; about 57.8% of this cost is borne by owners and operators during facility O&M [4]. These costs arise from inefficient business process management, redundant facility management systems, the cost of training on those systems, productivity loss, rework costs, and other issues [4] that BIM can address [2]; by offering owners and operators a powerful means of retrieving information from a virtual model of a facility, BIM can support and complement a wide range of information technologies used by facilities organizations [1].

Recent research has begun to explore how BIM can be leveraged to provide facility managers with a more automated approach to space management, capital planning, and asset management [5,6]. BIM can inform decisions on preventive maintenance [1,3,5,7], building systems analysis [5,6], and commissioning processes [5,6,8,9]. BIM can also be utilized to develop emergency planning and response strategies [2,5,10], as well as approaches to decommissioning and re-purposing [5,11,12]. To adopt BIM for FM in practice, the industry still needs to establish the economic value of implementing BIM for FM, identify the FM information needed to be included in BIM for different types of organizations, determine the tools available, workflow processes, and best practices, among other necessary metrics, parameters, and guidelines [5]. The information to be included in BIM is collected continuously, throughout different project stages and for different purposes [13,14]. This surfeit of pre-project and execution phase information in the BIM models delivered to facility personnel typically do not contain the necessary information for executing FM tasks [15]. In order to make BIM useful for facility managers or owners, project teams should define early on which FM information they need to include in their BIM models [15], and then establish a systematic process for capturing it during the design and construction phases.

The term “FM-enabled BIM” used in this paper refers to a BIM model containing required FM data for auto-populating computerized facility management systems (CMMS). This research discusses the implementation process for developing FM-enabled BIM in the context of a higher education institution. In such a setting, the major objectives of implementing FM-enabled BIM, as defined by the project, are to support

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FM tasks involving space analysis, retrofitting, and preventive maintenance.

In order to examine the current state of practice and determine future research directions, this paper presents the results of a broad literature review of BIM for FM and investigates a real-world implementation of FM-enabled BIM. Through the BIM implementation, the study closely examined the overall process of developing and delivering FM-enabled BIM models, identified the information required for these models, explored the strategies for capturing and transmitting FM data, uncovered the challenges faced during the BIM-enabled handover, and collected the bottom-line lessons learned on the project. Lastly, the researchers developed a strategic roadmap for future research to build and grow the knowledge foundation of BIM for FM.

2. Background and previous studies

Recent research has confirmed the commonly accepted belief that, with strategic planning, BIM implementation stands to be of great value to facilities management [16], since "the inherent complexity of FM presents opportunities for encapsulating rich semantic data within BIM" at the design and construction stages of a building life cycle [17]. The application of BIM technology in FM "varies depending on the organizational mission and the requirements of the facilities infrastructure supporting it," and the informational needs of different organizations are quite diverse [1]. With no standard process or set of best practices for creating an FM-enabled BIM model that addresses all the information requirements of different types of organizations, owners are often unsure of what BIM deliverables and processes demand [18]. Even though BIM models could support owners in FM-related tasks, facility managers do not normally use them, since they either do not contain the information needed [19], or in many cases contain superfluous information.

2.1. The required information in BIM needed for FM

In order to plan, develop, and deliver FM-enabled BIM, FM personnel must identify the required data for FM activities and define the desired levels of detail [14,20]. The Construction Operations Building Information Exchange (COBie) data format provides a standard for capturing and recording project handover data created during design, construction, and commissioning [21]. Because COBie allows for the storage of a vast amount of different types of data, filling in all the types of data fields would be overburdening [22,23]. Thus, in spite of the utility of the COBie format, identifying the required BIM data for FM activities remains a necessary and critical process [22]. Several studies have been carried out on this topic. After identifying the potential application areas of BIM for FM, Becerik-Gerber et al. [5] showed that each one of these areas is data-intensive and requires specific data requirements. They initiated a general approach of identifying data requirements [5]. To understand existing FM requirements and the types of maintainability issues that frequently occur during O&M, Liu and Issa [14] developed a survey questionnaire to collect input from industry practitioners. Their research resulted in the development of an initial list of maintenance problems that should be considered during the design phase [14]. Sattenini et al. [19] identified which information FM managers would like to see in a BIM model, and they carried out a university building case study to assess the performance of a BIM model with that information. To study the non-geometric building information needs for FM, Mayo and Issa [24] assembled a Delphi panel of facility management personnel to establish a list of final BIM products and their formats. In a university case study, Cavka et al. [25] identified types of information required by O&M personnel to perform maintenance, building systems monitoring, and manage assets. Lastly, ongoing research conducted by Dias & Ergan [15] is trying to identify facility managers' requirements on as-built BIM, with a focus on the maintenance of HVAC systems.

2.2. The strategies for capturing FM data during design and construction phases

Theoretically, an ideal BIM model should perform the following functions: hold information for different stakeholders throughout a facility's life cycle [13]; enable transference of facility information from the design and construction phases to the operations phase; and provide a reliable facility information database that gives facility managers integrated views from which to retrieve and analyze information efficiently [26]. However, in actual practice, at the handover phase, facility managers typically receive a large amount of information in paper or electronic documents, and must key relevant data into their computerized facility management systems [27]. A number of studies have been conducted to establish processes that realize the potential of BIM to support FM by capturing required data throughout the design and construction phases, and then formatting it for automatic importation into computerized facility management systems. Studying a university construction setting, Thabet et al. [22] proposed a BIM-FM workflow, according to which an owner uses standardized data collection to incorporate BIM facility information into project FM systems at close-out for improved efficiency and more accurate information. For BIM to include relevant building service information in a useable format, Tian and Liu [28] proposed a semiotics-inspired framework to extend BIM beyond a service-oriented perspective. Within this framework, IFC models are utilized for data exchanges [28]. Borhani et al. [29] studied the current information exchange best practices developed by academia and industry and proposed a workflow for BIM data transfer to asset management systems. Moreover, Orr et al. [30] developed a BIM-based workflow to capture object attributes and make seamless data transfers from BIM models into FM systems. This system was assessed for its applicability and flexibility in support of O&M practices within a university's FM department [30]. However, the workflow discussed in this research does not include the BIM model development process during design and construction. These studies indicate that capturing, storing, and transferring facility information cannot be optimized by the simple adoption of BIM as a new information storage tool; and they further show that project teams must also deploy a new BIM-enabled process that first captures project information and then exchanges it in an open data format, one that is potentially interoperable with different FM software applications.

2.3. Previous case studies

Table 1 presents a summary of the publications in which BIM models are developed to support FM in real-world projects. The table compares the following aspects of these real-world implementation cases: 1) the purpose of the case study; 2) the discussion of FM tasks supported by BIM; 3) the discussion of the BIM information needed for FM; 4) the process of developing the BIM for FM use, if any; and 5) finally, challenges and barriers. As Table 1 shows, few of the published case studies provides in-depth information on both "the required information in BIM needed for FM" and "the process of developing FM-enabled BIM." Even though theoretical research on these two topics has been conducted through surveys, interviews, and group discussions [5,14,15,19,22,24,28,30], and based on industry professionals' experience and beliefs, the findings have not been tested and examined within the context of real-world projects. Thus, the challenges and barriers associated with implementing the suggested methods and processes have not yet been clarified. This research aims to bridge this gap by presenting a pilot project on implementation of FM-enabled BIM, and by proposing a roadmap for future research in this field.

3. Research method

To date, very little empirical research has been conducted to determine how FM-enabled BIM can be developed during the earlier

Table 1
BIM-FM case studies.

Case study name	Year	Author(s)	The purpose of the case study (for testing technology or process, etc.)	The FM tasks that BIM supports	Required information in BIM needed for FM	Process of developing BIM for FM use during design and construction phases	Challenges and barriers encountered in the Case Study
An Anonymous Campus Building	2010	Akcamete et al. [31]	To assess the possible benefits of using BIM for maintenance planning	Using BIM to support identifying spatial trends for repair activities and spatial relationships between them	COBie is mentioned but not discussed in detail.	Not discussed	Briefly discussed
Auburn University's Construction Management Building	2011	Sattenini et al. [19]	To discuss the information needed by facility managers within a BIM model	Not discussed	Very briefly discussed. No required information list is proposed.	Not discussed	Not discussed
MediaCityUK project	2012	Arayici et al. [32]	To investigate how BIM can support effective and efficient accomplishment of FM tasks	Maintenance operations and space management	Not discussed	Very briefly discussed	FM challenges for the university and for the university building in MediaCityUK are discussed.
Texas A&M Health Science Center	2013	IFMA, Teicholz [1]	To demonstrate the process of capturing digital information about the spaces, systems, and equipment used for facility management.	Preventive maintenance and emergency situation regarding operations	Not discussed	Very briefly discussed	Lessons learned and areas of improvement are discussed in detail.
USC School of Cinematic Arts	2013	IFMA, Teicholz [1]	To provide an example of BIM FM practices; to summarize the progression of BIM-to-BIM-FM across construction; to "demonstrate the importance of focusing on information within the BIM process, as well as the need for integration and the user interfaces necessary to support the uses of this information for effective decision making"	Goals for BIM implementation are discussed in detail; several FM tasks supported by BIM are narrated.	Some issues of determining which data to collect are discussed, but the required information is not presented.	Software applications used in the BIM development process are discussed in detail, but the process of developing BIM is not discussed.	Challenges and lessons learned are discussed in detail.
Xavier University	2013	IFMA, Teicholz [1]	To describe the use, integration, and delivery of BIM through all stages of construction	Role of BIM in supporting FM requirements is discussed, but no particular FM task is specified.	Not discussed	Not discussed	Technical obstacles and lessons learned are discussed in detail.
An Anonymous Real Estate Development Organization	2013	Chunduri et al. [16]	To understand the effectiveness of the procedures outlined in the BIM Planning Guide for Facility Owners	Not discussed	Not discussed	Not discussed	Not discussed
Manchester Town Hall Complex	2014	Kiviniemi & Codinhoto [33]	To document some of the issues involved in the adoption of BIM in FM; to identify some of the enablers of and barriers to BIM implementation in FM.	Some FM services are listed and discussed.	Not discussed	Not discussed	Briefly discussed
Northumbria University's City Campus	2015	Kassem et al. [34]	To investigate the value of BIM and the challenges affecting its adoption in FM applications	Several FM tasks supported by BIM are briefly narrated.	Not discussed	Not discussed	Challenges are discussed.
University of British Columbia Campus	2015	Cavka et al. [25]	To understand the potential and the challenges of transitioning from a paper-based to a model-based approach in handover and facility operations.	Maintenance, building systems monitoring, and manage assets	Information needed for maintenance, building systems monitoring, and manage assets are listed	Not discussed	Challenges involved in transitioning from paper-based to model-based work flows and practices are discussed
Penn State University's Office of Physical Plant	2015	Terreno et al. [35]	To identify benefits gained from the effective integration of BIM in FM	Not discussed	Not discussed	Not discussed	Not discussed
An Anonymous Building	2015	Zadeh et al. [36]	To test the proposed BIM quality assessment approaches for FM	Not discussed	Not discussed	Not discussed	Not discussed
An Anonymous University	2016	Thabet et al. [22]	To investigate the specific challenges in determining facility information for use during facility operations and management	Not discussed	Briefly discussed	Proposed workflow is discussed	Not discussed
Three Anonymous Universities	2016	Terreno et al. [37]	To illustrate the key issues, considerations, and value to be gained from BIM integration into the FM phase	Not discussed	Not discussed	Not discussed	Briefly discussed
	2016				Not discussed	Not discussed	Not discussed

(continued on next page)

Table 1 (*continued*)

Case study name	Year	Author(s)	The purpose of the case study (for testing technology or process, etc.)	The FM tasks that BIM supports	Required information in BIM needed for FM	Process of developing BIM for FM use during design and construction phases	Challenges and barriers encountered in the Case Study
The Kerr Hall East building of Ryerson University		Khaja et al. [38]	To investigate parametric tools that automate information transfer between BIM models and FM systems	Space management, occupancy tracking, work order tracking, inspection record, report management			

stages of the building life cycle (i.e., design and construction). This research examines the planning and development of FM-enabled BIM in a pilot project to get rich insights into the implementation of an emerging BIM-based process—in this case, FM-enabled BIM—in a real-world context. Such in-depth insight cannot be achieved through general surveys of large sample populations [39]. Evaluating FM-enabled BIM implementation in a real-world context is crucial to capturing lessons learned and defining future research directions [39].

To develop an in-depth understanding of the project, we have acquired and studied a) the BIM contractual and implementation guidelines adopted in this project, which are discussed in Section 4.2, b) the coordinated BIM models for construction and the as-built BIM models of each discipline, which are discussed in Section 4.3, c) the owner's BIM component requirement documentation, which are discussed in Section 5.1, and d) the specifications pertaining to BIM data capturing and mapping to COBie format, which are discussed in Section 5.2. To fully understand the interoperability issue faced by the project team regarding to importing the COBie spreadsheet into the CMMS, we have also studied the project team's email records, the guide of importing COBie format spreadsheets into the CMMS, the testing COBie spreadsheet that has been successfully imported, and the final COBie spreadsheet that has not been imported successfully. In addition, we have observed the process of importing COBie spreadsheet into the CMMS. The difficulties and challenges of data interoperability issue are discussed in Section 6.1.

Semi-structured interviews with key stakeholders were carried out to get further insights into the process of developing and delivering FM-enabled BIM. Five of these interviews were in person, and six were online interviews. The stakeholders interviewed included the members of the institute's facilities department (seven individuals), the BIM consultant team (three individuals), the superintendent of the general contractor (one individual), the architect and mechanical engineer of the design company (two individuals), and the mechanical subcontractor (one individual). The first round of interviews took place in September 2013 and January 2014, before the project completed. Then, after the completion of this project, from October of 2015 to June of 2016, the researchers conducted follow-up interviews. These interviews were carried out to investigate the results of FM-enabled BIM implementation further, and to discuss the challenges and improvement opportunities for future advancement in the field. To ensure the objectivity of this investigation, the research team used a triangulation method that involved interviews with the following parties: i) a third-party software and consulting company whose software and service is centered on BIM quality assurance; ii) the owner and user of BIM data, which in this case was the facilities department of the institution; and iii) individuals involved in developing the BIM data. The interviews were conducted individually, and focused on each interviewee's insights on process effectiveness and lessons learned.

Although the questionnaire was developed to guide the interviews, the participants had the opportunity to discuss the project and the process from their own perspectives. Each interview took between 1 and 2 h. All the interviews were audio-recorded, and thematic analysis was carried out after the records were transcribed. The key pre-determined questions were designed to correspond to the themes studied, and included the following topics: 1) general project information; 2) the owner's objectives in implementing FM-enabled BIM; 3) BIM software applications adopted; 4) BIM model development process; 5) required information for FM; 6) the process of capturing, managing, and exchanging FM-related BIM data; 7) BIM-enabled handover process; 8) the infrastructure needed to implement FM-enabled BIM; and 9) challenges and lessons learned.

Fig. 1. The building studied.

4. Project information

4.1. Introduction to the project

This pilot study of FM-enabled BIM implementation was conducted at a public university recognized as a leader in research and technology development. In 2011, the institute established BIM requirements for awarding campus projects to design, engineering, and construction teams, with the aim of adding value to FM. The implementation of the requirements is mandatory for campus projects over $5 million, and encouraged for projects over $2.5 million. The project studied in this paper was the first to be subjected to these required changes in the process. Planned as a research facility, this project started in the summer of 2012 and was completed in September 2015 (see Fig. 1). It stands as a 200,000-square-foot state-of-the-art facility, having cost $113 million.

The building studied is a five-story structure that houses multiple disciplines, including chemistry, engineering, biology, and computational science. The building comprises research and laboratory space to support approximately 85 faculty members, 425 graduate students, and several hundred undergraduate students. It features cutting-edge, collaborative biology research laboratories for chemical, cell, and systems biology. Its basement level serves as a vivarium for medium- and large-sized animals. It also supports the administrative functions for the School of Biology.

The project delivery method was Construction Management at Risk (CM at Risk), which the institute had traditionally used for its new and major renovation construction projects. The Integrated Project Delivery (IPD) philosophy was used to establish early stakeholder collaboration. Because the owner is a state institution, a fully integrated contract between architect and the general contractor was not permitted. Nevertheless, implementing an IPD philosophy improved stakeholder collaboration and thus enabled the delivery an effective FM-enabled BIM model. Moreover, to ensure the successful creation of the model, the owner required project teams to be knowledgeable and proficient in BIM. The level of BIM expertise was an essential criterion in the process of awarding contracts to architects, engineers, and contractors.

4.2. Owner's business objectives in implementing BIM for FM

The institute was in the formative stages of developing an approach to implementing FM-enabled BIM, having developed the following goals: 1) to capture FM information during the project development phase; 2) to extract project information in a useable format compatible with FM systems; and 3) to use the model geometry and data for space analysis, retrofitting, and preventive maintenance. On this project, the FM information in the BIM model was useful in a number of ways: 1) to verify the design solution against the program; 2) to provide scheduled building equipment/component lists; 3) to determine construction submittal register requirements; 4) to identify installed equipment and all tagged building products; and 5) to specify close-out deliverables. The initial plan was to deliver project information in a usable format such as COBie and then import the data into the AiM system (the institute's CMMS platform).

The institute developed and published three major sets of guidelines to provide a framework in which the owner, architect, engineer, and construction manager could effectively and efficiently deploy BIM technology and best practices: 1) *BIM Requirements & Guidelines*, which prescribed the overall BIM requirements, the BIM implementation process, the objectives and applications of BIM, and the data ownership and rights [40]; 2) *Architecture and Engineering Design Standards for Building Technology*, which specified the official architectural and engineering requirements, and provided the required design standards to support O&M activities [41]; and 3) *BIM Execution Plan*, which identified the core collaborative team members (or key stakeholders) and specified their roles, responsibilities, company information, and contact information [42].

4.3. BIM model development

The major BIM software tools used by the design and construction teams were Autodesk products, which included Revit Architecture, Civil 3D, Revit Structure, Revit MEP, Navisworks, and BIM 360 Field. They also adopted IES VE-Pro and EQuest to develop the Energy Analysis Model. During the design phase, the design team used Revit to develop the initial design BIM models—i.e., the architectural, lab furnishing, and MEP models. The civil engineers provided 3D topography and site utility information within five feet of the building's perimeter and developed the 3D site model in Autodesk Civil 3D. The energy analysis team developed the energy model in IES VE-Pro and used it to perform energy analysis and life cycle costs analysis.

The general contractor involved the key MEP subcontractors (e.g., mechanical, plumbing and electronic controls) and the structural subcontractor early in the design phase. The superintendent merged all the design models received in the Navisworks platform, coordinated them, provided feedback to the designers, and then detected and resolved clashes. Later, during the construction phase, the subcontractors developed the as-built BIM models of their disciplines, while the architects developed the architectural as-built BIM model (Fig. 2). BIM models were then imported into BIM 360 Field, which the general contractor used to track all equipment information, such as installation dates, warranty information, and bar code information. BIM 360 Field can also export spreadsheets with building component information. In the handover phase, the BIM deliverables were Autodesk Revit, Navisworks files, and spreadsheets in the COBie format to facilitate data transfer into an FM database. Fig. 3 illustrates this process of development for as-built BIM models.

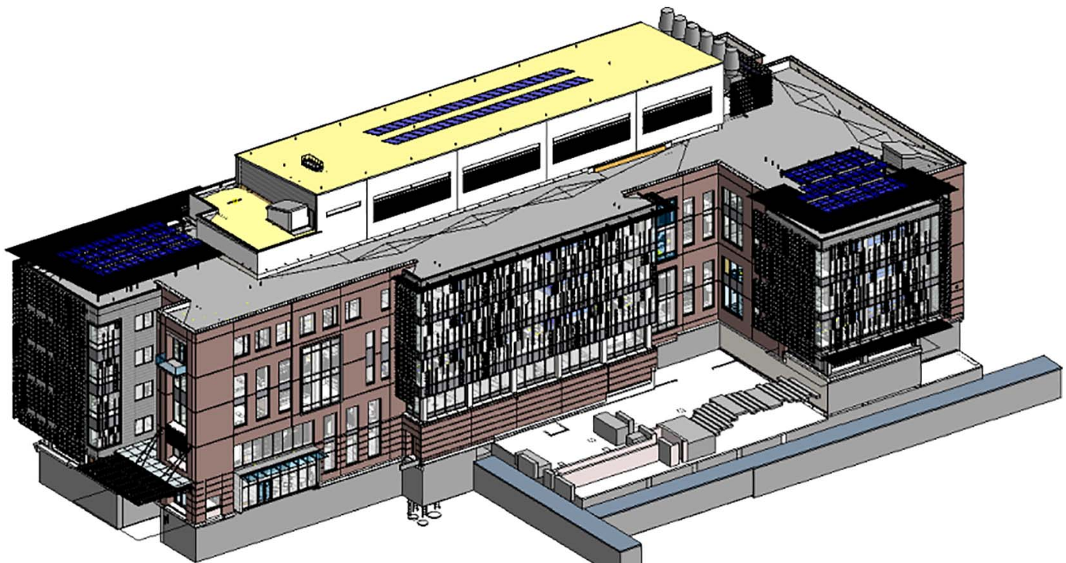


Fig. 2. As-built BIM Model.

5. Implementing FM-enabled BIM

5.1. Required information for FM

The project team aimed to create an as-built BIM model that could serve as a central facility data repository for FM task support. Prior to commencing the project, the institute's FM team developed the *BIM Component Worksheet*, as a baseline inventory list for model components. This worksheet generally specified which assets should be tracked through BIM during the design and construction phases [43]. The asset list was divided into eight categories: 1) Site; 2) General (Footprint, Exterior, Interior, Windows, Circulation, Restroom, Kitchen Equipment, Rooftop, and Reflected Ceiling Plan); 3) Specialty Equipment; 4) Furniture; 5) Structural; 6) Mechanical; 7) Electrical; and 8) Plumbing.

In the absence of any standard, owners typically collect as much information as possible [24]. However, on this project, the institute's FM team determined in advance which information was imperative to the building's BIM model for building maintenance. Working with the BIM consultants, the team developed the required information list that specified the major assets for maintenance (Table 2) [44]. The project team used this list to determine the key building components that should be tracked during the project development phase. The OmniClass standard was adopted to categorize these components in the model.

Additionally, the *BIM Requirements & Guidelines* specified the particular parameters or the field of data that should be tracked for each building component, as shown in Table 3 [40].

5.2. Capturing, managing and exchanging FM-related BIM data

The COBie approach was prescribed for capturing the base data for

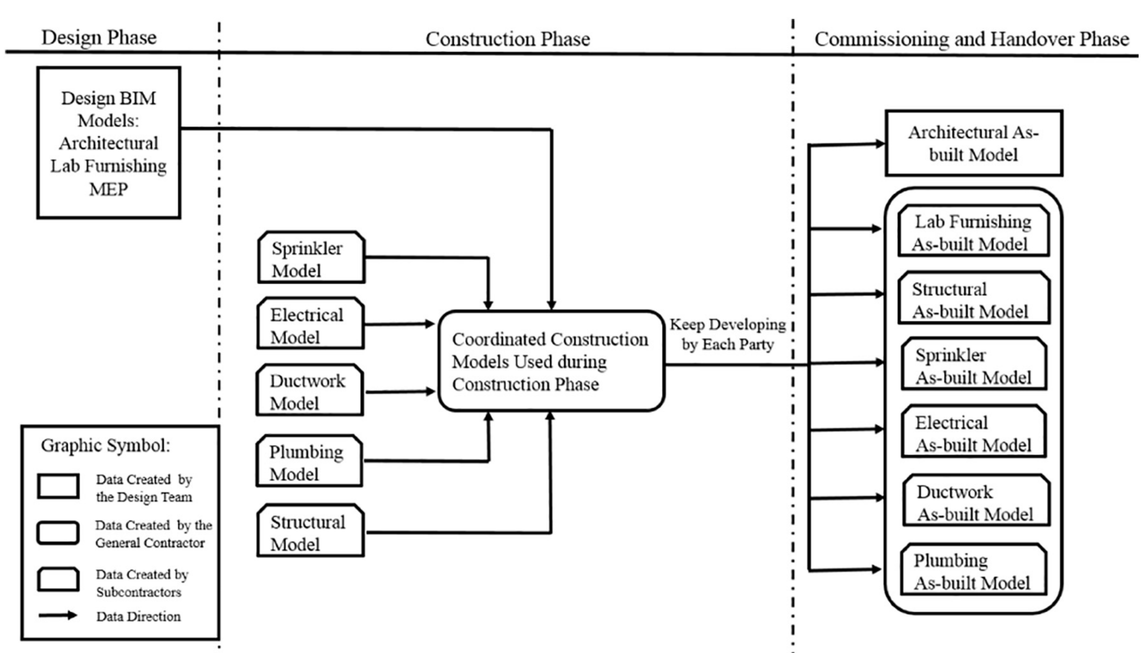


Fig. 3. Development of as-built BIM models.

Table 2
Major assets tracked through BIM [44].

OmniClass	Asset
23-13 39 31	Roof membranes
23-23 11 11	Elevators
23-25 69 11 15	Laboratory fume hoods
23-27 17 00	Pumps
23-27 21 00	Compressors
23-27 29 00	Tanks and storage structures
23-27 31 00	Valves
23-27 31 11	Backflow preventers
23-29 37 13	Emergency eyewash stations
23-29 37 13 15	Combination emergency eyewash stations
23-29 37 13 17	Dedicated emergency eyewash stations
23-29 37 15 13	Dedicated emergency showers
23-31 29 00	Hot water heaters
23-31 31 00	Drinking fountains
23-33 11 00	Commercial boilers
23-33 11 15	Fire tube boilers
23-33 21 00	Chillers
23-33 25 00	Air handling units
23-33 25 15	Heating and ventilating units
23-33 27 15	Air humidifiers
23-33 31 15	Exhaust hoods
23-33 31 19	Fans
23-33 33 11	Fan coil units
23-33 37 00	Refrigerant condensing units
23-33 41 17	Terminal air units
23-33 41 17 13	Variable air volume terminal units
23-33 47 00	Air dryers
23-33 49 23 15	Return air grilles
23-33 49 23 13	Supply air grilles
23-33 55 00	Energy HVAC recovery equipment
23-35 11 00	Electrical generators
23-35 13 00	Transformers
23-35 31 00	Electrical power distribution devices
23-35 31 29	Switchboards
23-35 31 31	Switchgear
23-35 47 11	Lighting fixtures
23-35 47 13	Emergency lighting
23-35 47 15	Exit illuminated signs
23-39 29 00	Waste water collection and removal
23-33 49 23 11	Exhaust air grills
23-27 23 15	Shell and tube heat exchanger
23-27 23 13	Plate frame heat exchanger
23-33 31 15	Relief hood
23-33 15 17 15	Unit heaters
23-33 15 21 13	Fin tube radiation
23-33 39 21	Split system AC units

Table 3
Tracked information of each building component [40].

Data requirements	COBie fields	
	Tab	Column
Asset tag	Component	Tag number
Asset description	Type	Name
Asset type	Type	Asset type
Asset group	Type	Category
Status code	Internal[a]	Internal[a]
Region code	Internal[a]	Internal[a]
Facility identification	Facility	Site description
Building name	Facility	Name
Floor identification	Floor	Name
Location identification	Component	Space
Shop location	Internal[a]	Internal[a]
Lockout	Internal[a]	Internal[a]
Manufacturer	Type	Manufacturer
Model	Type	Model number
Serial number	Component	Serial number
Warranty start date	Component	Warranty start date
Warranty expiration date	Type	Warranty duration parts

[a] Fields created by the institute.

O&M functions (e.g., contact, space, floor, or warranty). Since, by virtue of its categorical structure, the COBie-based system tracked data exports from the model and, thus, simplified the work required to capture and record project handover data. This efficiency reduced the loss of essential building information. At the beginning of the project, the BIM consultants provided a Revit template file in which various fields were to be populated with COBie data parameters. Designers and builders who worked on the Revit files were able to input required COBie data by filling in those blank fields with element properties, while creating and modifying the BIM models. The Revit models were the repositories of all required FM data throughout the design and construction phases.

The AiM system (CMMS) used by the owner only accepted the COBie 2.3 and 2.4 data formats. Initially, since the team lacked a tool that could directly generate COBie format data at the early design phase, it used BIMLink to extract selected project information from the Revit model and export it into a prepared Excel file. Once in the Excel format, the parameters from Revit model were then manually mapped onto a COBie format spreadsheet. Later, during the project development phase, Autodesk released the COBie Extension for Revit, an application that was COBie 2.4 compliant. Using this new tool, the team was able to generate the Excel spreadsheet automatically with COBie format data, thereby eliminating the error-prone manual element of data transition. Fig. 4 illustrates the BIM-enabled workflow used on this project to capture, manage, and exchange project information throughout the life cycle of the project.

The team also used BIMLink to import the data back into the Revit model after it had been extracted, and, further, to add more data. The input formats for the Revit model was Industry Foundation Classes (IFCs) and OmniClass for designating spaces and building assets. These formats requirements were established by the owner's facilities management department. The OmniClass attribute fields in Revit were consistent with data fields on COBie worksheets. BIM model managers were responsible for continuously tracking and meeting the requirements of the data transfer between the model and the COBie spreadsheet. Although the whole information-capturing process seemed to go well during the design and construction phases, the team faced an unexpected issue when importing the COBie format data into the AiM system in the handover phase. Section 6 provides a discussion of this issue.

5.3. BIM-enabled handover

One of the owner's goals was to use the BIM model to develop the building equipment list, in addition to verifying closeout deliverables and tracking the installed and tagged equipment. This list was based on a barcode system in which the barcodes of tagged equipment were consistent with the codes in the BIM model. Moreover, the general contractor had used BIM 360 Field to track all the equipment information during construction. Eventually, the final building equipment list was generated automatically by exporting the spreadsheets from BIM 360 Field.

It was anticipated that COBie would facilitate the smooth exchange of facility information into the CMMS, which was AiM in this pilot project. In the traditional approach, it would typically take months to input project information manually into the FM systems. During the construction phase of this project, the BIM consultant team keyed in the equipment information into the BIM (shown in Table 3). Typically, the FM team would start identifying and tracking this information during commissioning and occupancy. Moreover, the barcode system used during construction included building components that normally only the FM team would tag, barcode, and then record (e.g., VAV boxes and diffusers). The BIM consultants worked with the general contractor to develop a process for the FM team to tag that information digitally in BIM 360 Field and then generate serial numbers and bar codes for the list of items to track. Once tagged BIM 360 Field, the list would be imported directly into the AiM system. Therefore, most of the work that

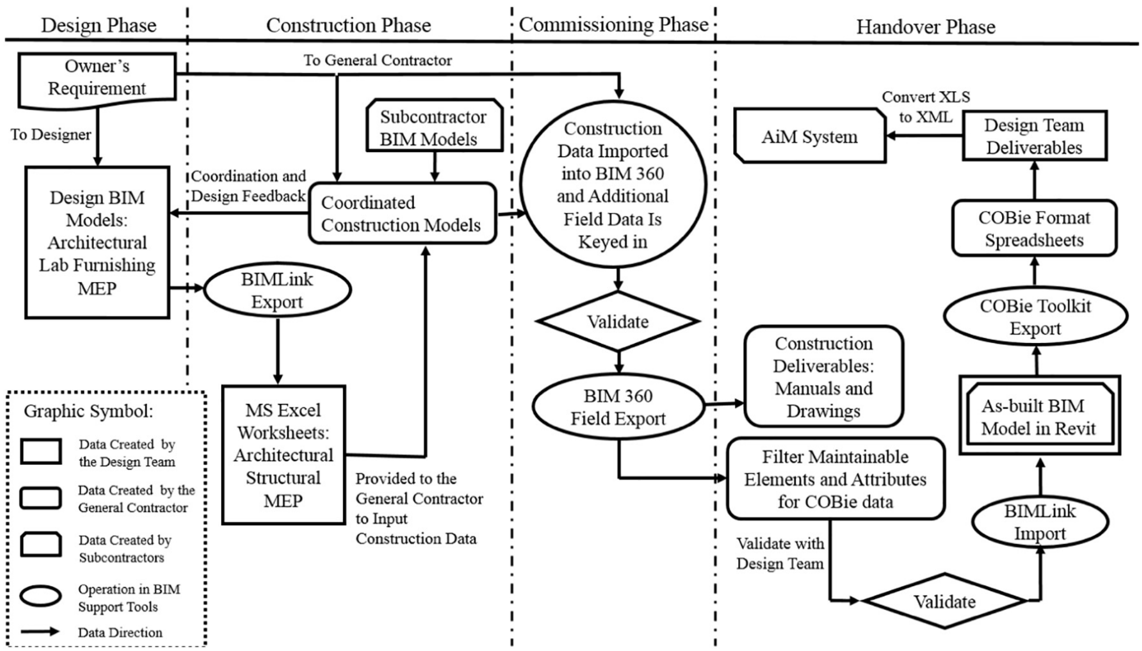


Fig. 4. The FM-enabled BIM workflow used in this project for capturing, managing, exchanging project information.

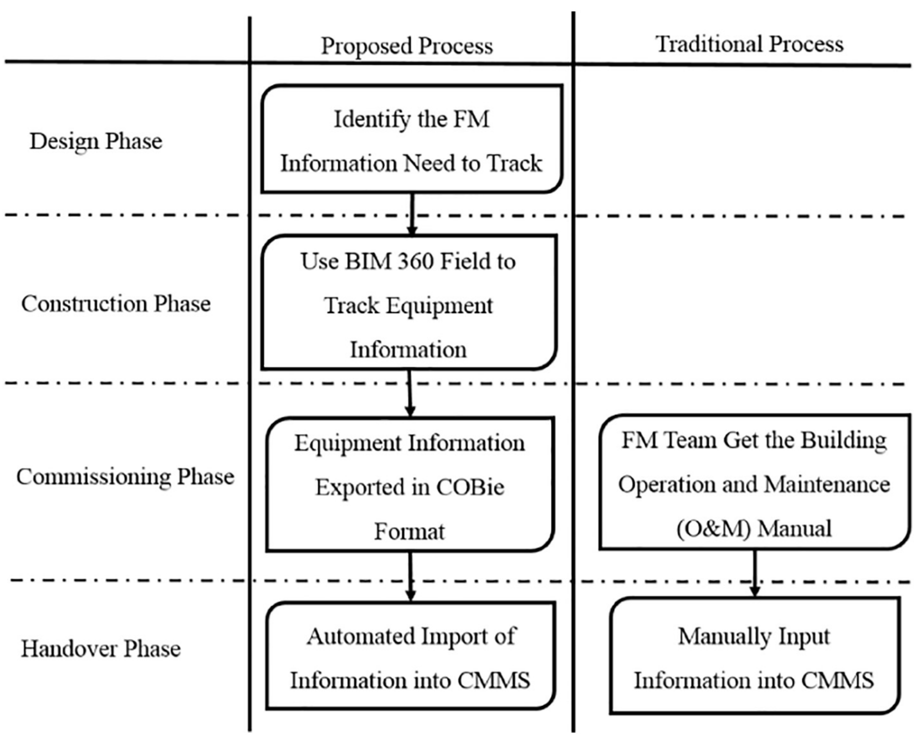


Fig. 5. Comparison of BIM-enabled equipment information handover with traditional handover.

the FM team would normally initiate once the building was occupied was already in progress and essentially complete during the handover process (see Fig. 5).

In this project, the general contractor and the BIM consultant team received the O&M documentations (hardcopy, CAD files, PDF, etc.) during the construction and handover phases. They studied the documents and input the tracked information into the BIM. The project team did not include or link the O&M full documents to the BIM. They numbered those documents based on the building system and component serial number. After the handover, the facility managers uploaded the documentations to the AiM system directly. This work was accomplished efficiently because AiM was already populated with the asset information tracked through BIM. All the facility managers needed to do were opening the asset information page in AiM and finding the relevant document to upload.

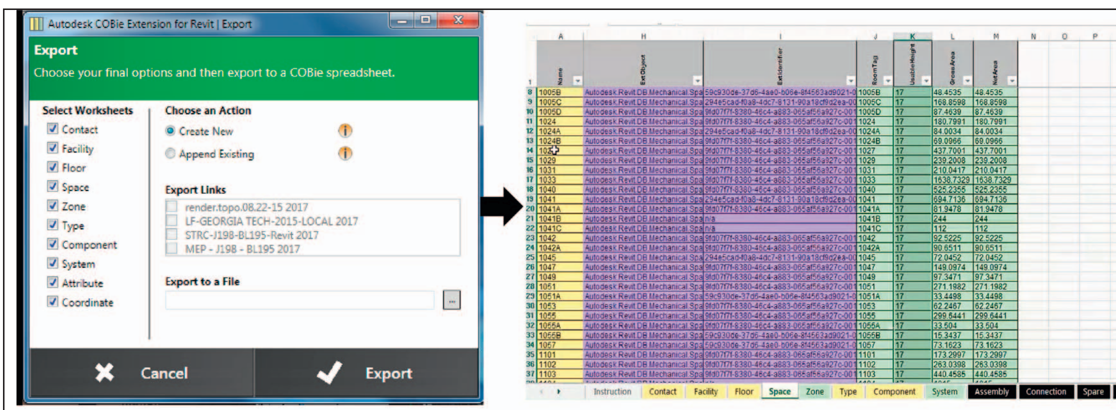
The closeout materials contained a number of BIM-based deliverables: the architect's record models with an LOD of 300; the as-built models up to 500 LOD; the COBie spreadsheets exported from as-built BIM models; and other supporting deliverables, such as manuals, warranties, and 2D drawings, both in digital format and hard copy.

6. Discussions: challenges faced and lessons learned

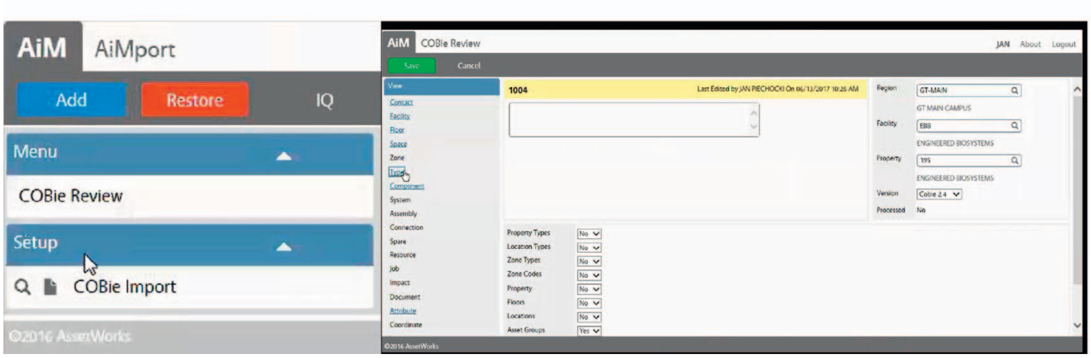
Even though BIM had been implemented on this project to improve

Step 1: COBie Extension Setting and Parameter Mapping

Fig. 6. The process of importing COBie formatted spreadsheets into the AiM system.

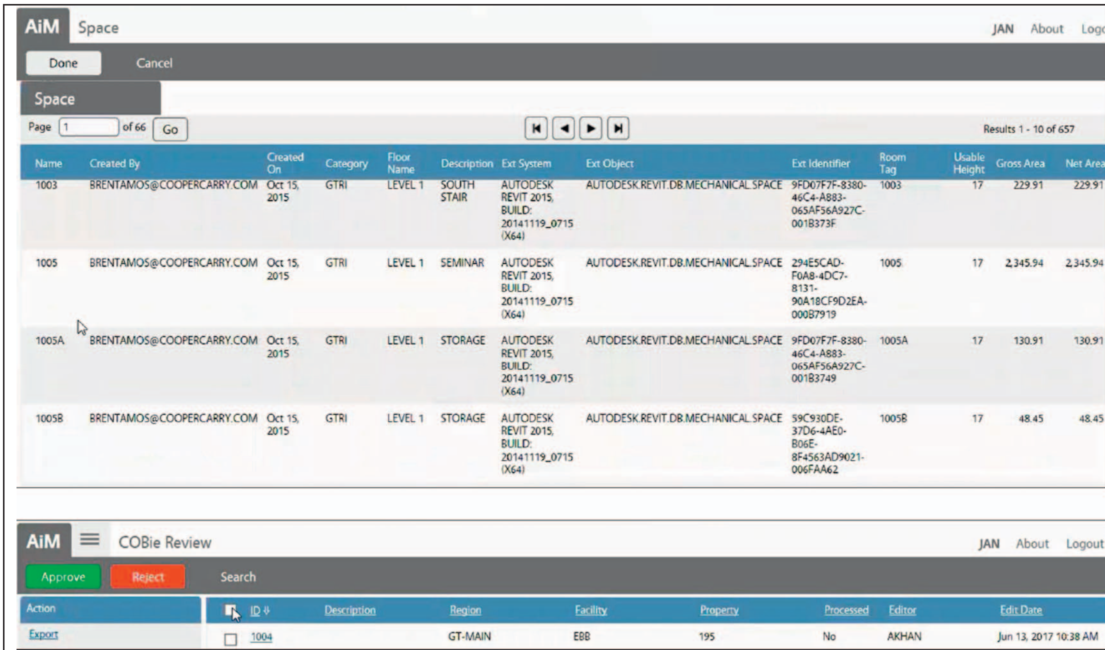


Step 2: Exporting COBie Formatted Spreadsheet



Step 3: Importing COBie Spreadsheet into AiM

Fig. 6. (*continued*)



Step 4: Review and approve changes to AiM

Fig. 6. (*continued*)

the efficiency and quality of design, construction, and facility management, the time constraint imposed on this highly demanding and complex project make this first-time implementation of the new FM-enabled BIM process challenging.

6.1. Challenges of importing data from BIM into CMMS

The only outstanding issue was with the use of the COBie toolkit to automate the data exchange from BIM into the computerized maintenance management system (in this case, the AiM system). The original plan, as Fig. 6 shows, was to export COBie spreadsheet from the as-built Revit model with the COBie Extension, and then import the COBie spreadsheet into the AiM system. However, by the end of the construction phase, every time the IT specialist on the FM team tried to import the COBie Excel spreadsheet into the AiM system, errors automatically halted the importing process.

When the imported data format from the COBie spreadsheet is not 100% complied with AiM system, the importing would be automatically stopped. Even though theoretically the data format exported by COBie Extension for Revit was COBie 2.4, which AiM system was complied with, the project team continually faced errors when attempting to import. Some of the errors were caused by "invalid value for certain attribute" in the COBie spreadsheet, for example, a field called "usableHeight" was input by the value of 16′-6″, but this field in AiM had to be numeric, which meant no apostrophe, dash or quote was allowed. Another type of error happened when AiM was trying to add information to a certain field but cannot find anything in the corresponding location of COBie spreadsheet. For example, if AiM was trying to acquire a manufacturer's email but the relevant spreadsheet cell was empty, then the program would try to access a value from null. This would trigger an exceptional event that disrupts the normal flow of the program's instructions. In addition, AiM has predefined parameters and syntax that are not generally known by non-AiM-experts and meeting those requirements are necessary for importing the COBie spreadsheet. For example, AiM requires the spreadsheet cells in the "Asset type" column have a predefined parameter, such as "SERIALIZED"; this is not a COBie standard but a requirement of AiM importing function. The project team did not know all these potential issues before they encountered the errors.

The interoperability issue caused a delay in transferring the FM information into AiM system during handover phase even though the data required by the owner's FM personnel was available in the BIM model. The project team had been very cautious about interoperability issues between different software programs from the very beginning of the project, and established naming conventions, but still was faced with the issue that nobody foresaw. These problems were not detected when data exchange test was performed by the BIM consultants during the construction phase. In the end, although the spreadsheet exported from the BIM model was in COBie 2.4 format and the AiM experts from AssetWorks provided support when the interoperability issues arise, the team find it time consuming to determine and address all sources of data transfer issues. If the facilities' data managers together with the IT support of the CMMS had specified the detailed data format requirements compatible with CMMS at the onset of the project, this interoperability issue could have been avoided. This is a major lesson learned by the project team. In the future, the data formatting requirements compatible with the selected CMMS should be incorporated in the FM-enabled BIM guidelines and communicated with the project team at the onset of the project.

As the project was approaching the operation phase, and the project data needed to be present in AiM, the team had no choice but to find another way to transfer the data and complete the task. They used a program named Pentaho to extract data from the Excel spreadsheets provided by the general contractor and import it to AiM system. That process, however, involved additional work and manual process and took relatively longer time because only a small amount of data could be imported at a time.

6.2. Fully integrating O&M documents with BIM

In this project the team did not fully integrate O&M documents with BIM. The team only keyed in BIM the essential building component information (as shown in Table 3). As the team received O&M documentations in both hardcopy and digital format (CAD files, PDF, etc.)

during construction and handover phases, they numbered those documents based on the building system and component serial number. After the handover, the facility managers uploaded the documentation to the AiM system directly.

To further integrate BIM and O&M data in future projects, the digital O&M manual can be broken down and linked to the corresponding BIM objects. If the O&M documents are stored in an online server, the Uniform Resource Locator (URL) could be used to link the O&M documentations with the corresponding BIM objects. The URL information could be easily transmitted from BIM to COBie spreadsheet, and then to AiM system. This way BIM and O&M documentations are integrated and the facility managers can access the O&M documents more efficiently.

6.3. BIM data quality control

6.3.1. Challenges in data validation

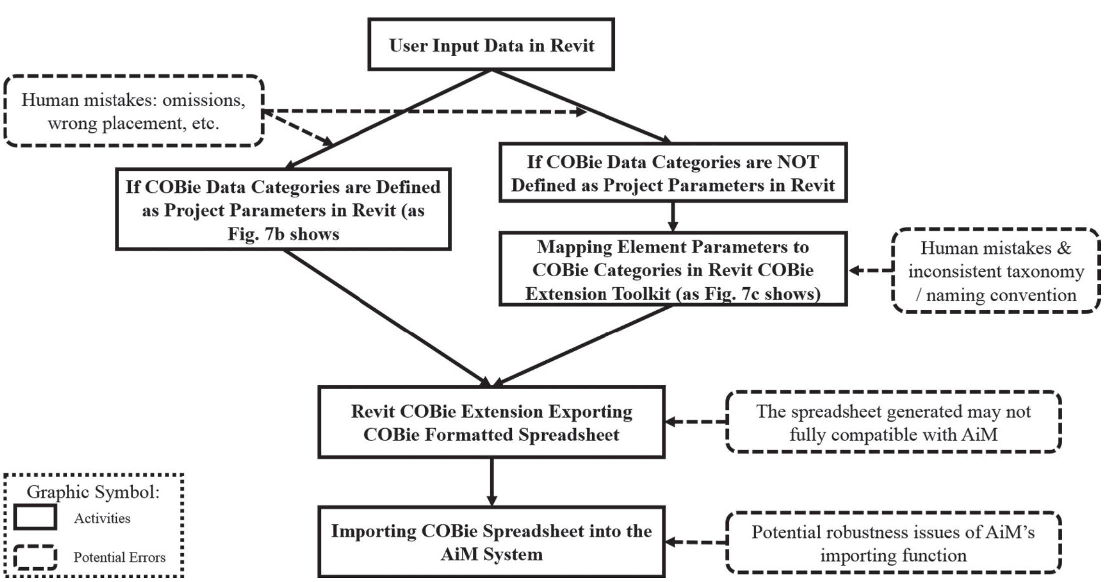
The necessity of BIM data quality control and assurance is a major lesson learned in this project. It is critical that BIM deliverables are continuously assessed to determine whether the required data are, in fact, in the model, whether their formats are correct and meet the requirements of the data user, and whether their qualities meet the stated requirements. Owners must check the data at least at every major project milestone. Towards the end of the project, the data should be checked more frequently.

In this case, even though no problem was detected when the BIM consultants performed the data exchange tests at the beginning of the project, the final COBie spreadsheet exported from the as-built BIM model was not compatible with AiM. The challenge is that many non-standard data input during the project development process could lead to interoperability issues during the handover phase. Fig. 7 shows the data transmission flow and potential errors. The most common and unavoidable errors are the ones caused by human mistakes. When developing the model, designers and builders may input wrong information or forget to provide input to the required COBie field of element properties. In this project, the COBie data categories, such as Asset Identifier, Contact, Manufacturer, were defined as project parameters in Revit. This allowed the modelers to input COBie standard information in the relevant property fields for each of the model element, as Fig. 7b shows. If the COBie data categories were not defined as project parameters, the COBie Extension toolkit can still map other property fields to the cells of COBie formatted spreadsheet, as Fig. 7c shows, but this may lead to errors when the information pulled from other property fields has a different taxonomy or naming convention. For example, Contact field for a piece of equipment in COBie should be formatted as “404 123 4567” but if the contact property for this element is formatted as “404-123-4567”; the mapping process may lead to future errors if the system that will use the COBie data requires the space rather than the hyphen between numbers. Normally, the COBie Extension toolkit and similar programs are not designed to comply with a particular CMMS, but they comply with an open standard such as COBie 2.4. Even when the information in the model are complete and correct, and the output data is compatible with the open BIM standard, the output may still not be fully compatible with the CMMS that will import the COBie data, as demonstrated in Section 6.1.

6.3.2. Methods of data validation

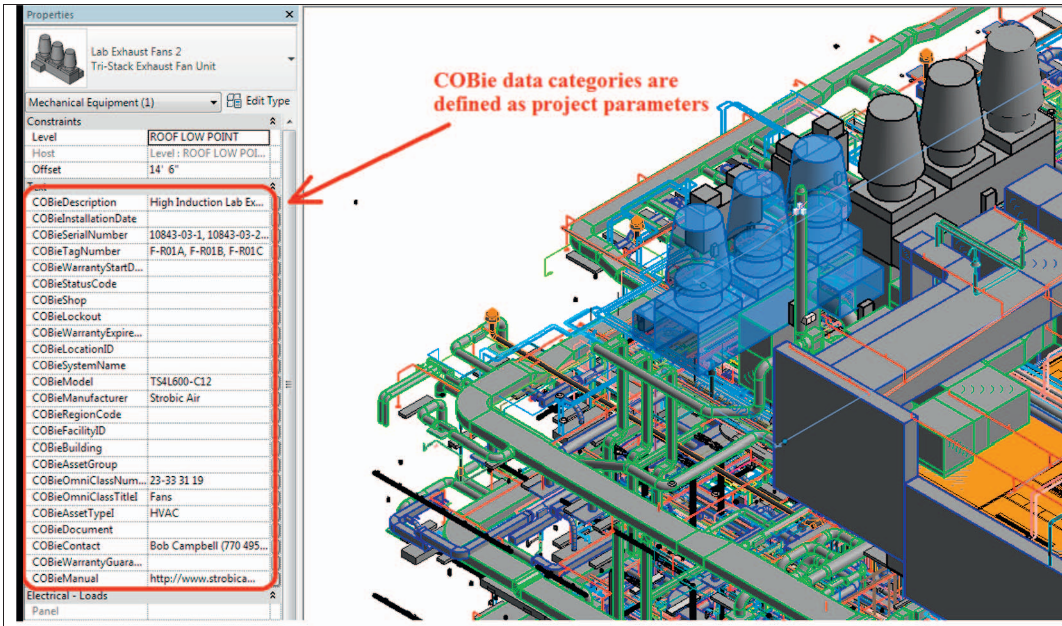
One method of validating the data in a BIM model is to check the model components in the BIM authorizing tool (e.g., Revit). However, manually reviewing thousands of components with multiple parameters can be labor-intensive, inefficient, and prone to omission. Moreover, the owner has to hire personnel with relevant BIM modeling skills to perform the work. Supporting software tools have recently been developed to enable inexperienced users of BIM perform BIM data validation [45–49]. With such software tool, a user can set up the BIM-based requirements for handover and data qualities, to validate the imported data from the BIM model (Fig. 8). The user then creates rules for checking the parameters of model components, and analyzes the model against these rules to determine whether the requirements have been met. The rules can be set to verify whether the properties are present and have values, and whether the values of the properties fall within a certain range. After conducting this quality control check, the user uses the software tool to list and count the components that do and do not meet the rules, and to highlight any selected components in a 3D view. In this way, the user/the author of BIM models can check the component properties and fix any problems efficiently. Once the necessary changes have been made, the corrected information can be imported back into the BIM authorizing tool.

One recently published study introduced a framework for understanding and assessing the information quality of BIMs from the FM perspective [50]. Using the framework, the project team can define the information requirements and perform data quality tests throughout

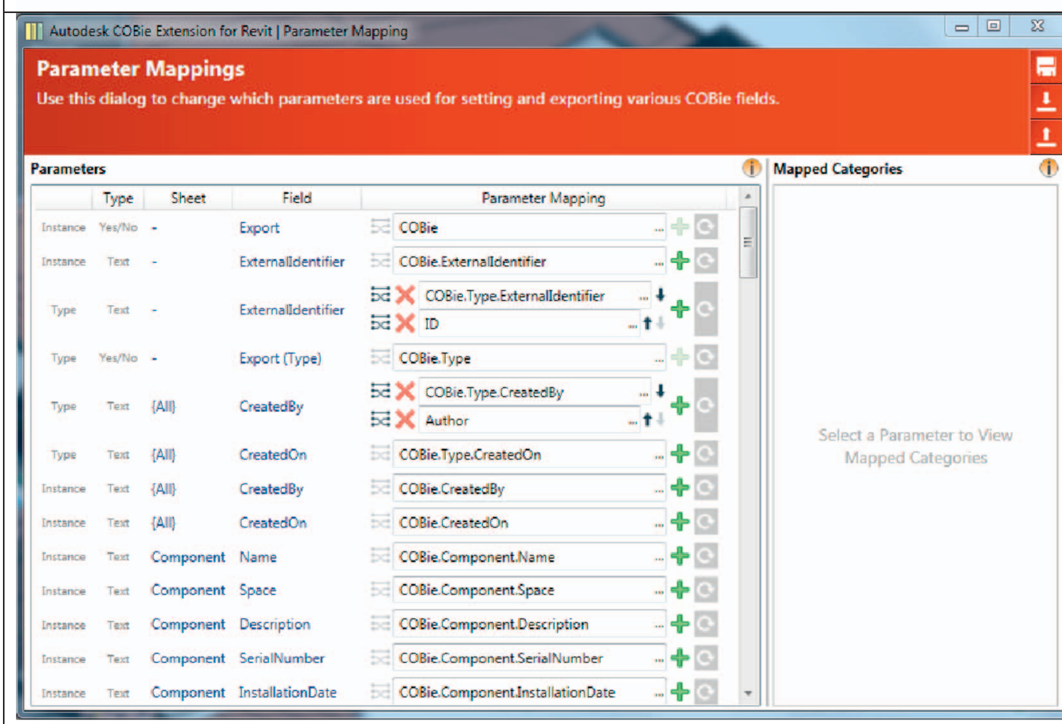


a: Data transmission flow and potential errors

Fig. 7. Data transmission flow and potential errors.



b: COBie Data Categories Defined as Project Parameters in Revit



c: Mapping Element Parameters to COBie Categories in Revit COBie Extension Toolkit

Fig. 7. (*continued*)

different project phases to ensure delivery of a have higher quality BIMs [50].

6.4. Allocating enough resources to BIM related activities and securing commitments

The need to allocate enough skilled resources to implement BIM-related tasks was another lesson learned on this project. Indeed, it was a problem that some of the project parties were not as involved in BIM implementation as others. Even though all participants were informed of the owner's expectations on BIM implementation, some underestimated the level of effort needed and did not assign enough resources to meet their commitments on schedule. A typical scenario was one person would be assigned as the BIM manager to handle everything related to BIM, including creating the model, reconciling clashes, creating drawings, and, in some cases, also managing the physical project execution. That was a tremendous amount of work for one person. It is not a good practice to assign one person to manage both

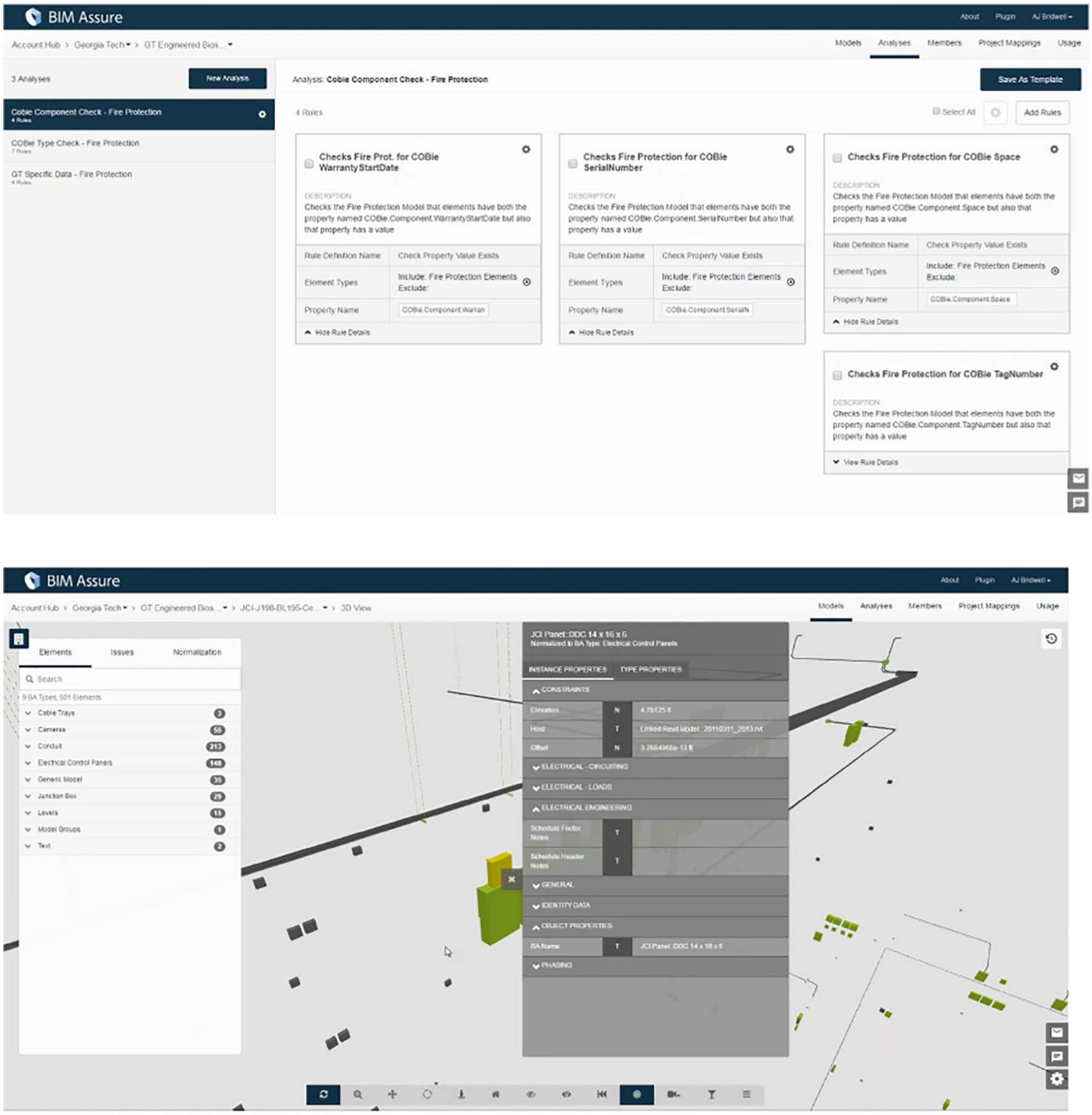


Fig. 8. Automated data validation [45].

virtual and physical aspects of a project implementation. Having adequate resources with the right expertise must be assigned to BIM positions. Furthermore, additional time must be built into the schedule for BIM quality control.

This research showed that having a BIM coordinator or BIM facilitator is essential, especially when the project team is implementing new tools and processes. Assigning a BIM implementation champion to represent the owner, from the beginning of the project to the end, will prevent stakeholders from falling into their traditional silos and work processes, and will ensure that they collaborate at a consistently high level throughout the project life cycle. This BIM coordinator or facilitator manages the horizontal integration of BIM data across different project phases, safeguarding its taxonomy and format consistency. This data management/quality control function is critical, since the entire project team must handle constantly evolving data across the project life cycle (see Fig. 9).

On this project, the BIM consultants were not hired as data managers responsible for the data validation process. The lack of a BIM/data integrator led to the failure of the automated data exchange process during the handover phase. Making matters worse, the BIM consultant went through a staffing change, and a new representative took over in the middle of the project, after the general contractor had configured the BIM 360 Field. This cold handoff created an additional burden on the project, since the new BIM consultants had a different view of how BIM 360 Field could have been set up to make the data exchange process seamless.

6.5. Integrated project team

Even though this CM at Risk project implemented some IPD principles, it still faced some coordination and collaboration challenges, which could have been overcome if the IPD model had been fully implemented. To collect and share FM-enabled BIM data seamlessly throughout the project life cycle, the owner/FM team, designers, general contractor, key subcontractors, and BIM consultants must all collaborate at a high level, from the beginning of the project to the end.

The IPD setting and contract type of this project necessitated early engagement and data-sharing among key stakeholders. The process used to create BIM models occasionally lacked efficiency because both the architect and general contractor duplicated some modeling efforts. Simultaneous modeling was necessary because the general contractor used BIM models that had been created by subcontractors who had not

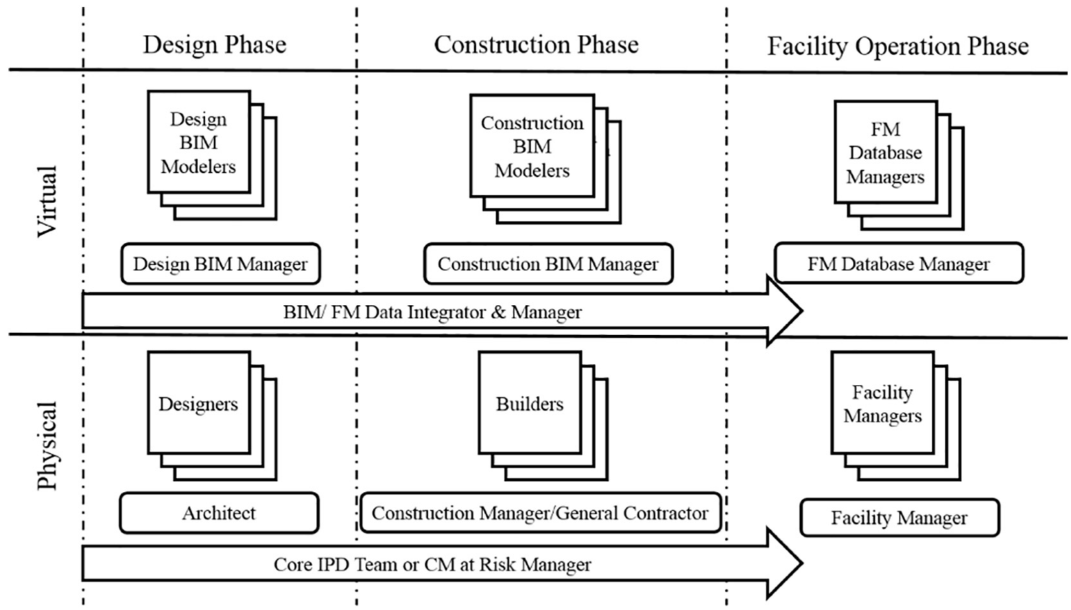


Fig. 9. Virtual versus physical managers and the need for project life cycle integration.

contracted with the design companies. Since they lacked a direct contractual relationship, the data-sharing between them was unavoidably delayed. Had the project been based on a multi-party IPD contract, its fully integrated team would not have had such contractual silos and, thus, would have maximized the efficiency of the data-sharing process.

In addition, an IPD delivery model would have facilitated the establishment of a more realistic schedule by ensuring input and buy-in from all key stakeholders, including trades and suppliers. The IPD model would also have mitigated the occurrence of change orders by establishing early involvement of key stakeholders, since early engagement enhances understanding of the project and increases collaboration from the beginning of the project. The challenges faced in this project, resulting from unrealistic initial schedule and change orders, could have been significantly mitigated if the IPD model had been fully in place.

7. Conclusion

Successful implementation of FM-enabled BIM can be achieved with 1) a clear definition of what FM-enabled BIM constitutes, 2) a seamless and practical process of collecting the FM-enabled BIM data throughout project development phases, and 3) a well-executed interoperability plan for exchanging data between BIM tools and facility management systems, such as CMMS. This research examined a real-world FM-enabled BIM implementation on a university research building project, to determine the information required for FM-enabled BIM, to articulate the process of gathering, managing, and exchanging FM-related BIM data, to identify the challenges faced during the BIM enabled handover, and to capture lessons learned.

FM-enabled BIM implementation is the process through which essential facility information is captured, maintained, and shared digitally in a set of integrated BIM models. At the handover phase, this process ensures that important project information is readily available to auto-input into the relevant CMMS. Through FM-enabled BIM, maintenance personnel have access not only to FM information, but also to the geometrical BIM model, which provides information such as equipment location, accessibility, and maintainability.

This research examines a proposed BIM-enabled workflow to capture, manage, and exchange project information throughout the life cycle of a project. Some of the BIM-enabled practices implemented on this pilot project have also been suggested by previous research. These practices include the following: the need to identify BIM Information needs for FM [5,24]; the importance of using COBie as the data exchange format [27,51–53]; the usefulness of BIM 360 Field during construction [54]; the efficiency of a barcode system that gives tagged equipment BIM model codes [55,56]; and the value of BIM-enabled handover [53,57]. Even though the data transfer during the handover phase of this project was not fully automated, it provided an invaluable insights and learning experience to all the participants.

The major lessons learned on this project include the following: 1) involving the facilities data manager and the CMMS IT specialist at the onset of the project to specify the data formatting requirements compatible with the selected CMMS, incorporating such requirements in the FM-enabled BIM guidelines and communicating it with the project team at the onset of the project; 2) creating models in BIM authoring applications, rather than importing models from non-BIM applications into BIM applications that use IFC formats; 3) conducting continuous BIM data quality control and assurance throughout the project; 4) allocating enough resources to BIM-related activities; 5) establishing a fully integrated project team, consisting of representatives from the design, construction, owner organizations, as well as the data facility manager; 6) avoiding projects with tight schedule when implementing a new technology and workflow process, a team should build enough time into the project schedule to overcome any unexpected issues.

These lessons learned are the unique contribution of this study and are widely generalizable to all variety of projects. Some of the details presented in this pilot project (e.g., FM tasks, BIM authorizing tool, and FM System) may be limited in how much they apply to a specific project type, and may only be applicable to projects with similar attributes. Future research is needed to tackle each of these aspects and variations of FM-enabled BIM workflows; it must define and establish the appropriate data requirements and interoperability needs and procedures for each project type, FM task, BIM authoring tool, and FM system. Different data and interoperability needs and procedures must be defined and established. Based on the insights gained from this research, the authors developed a framework for future research in BIM for FM (see Fig. 10).

The proposed road map in Fig. 8 provides a framework for future researchers to carry out in-depth single case studies to collect information and provide insight into the new field of BIM for FM, by addressing the following objectives: 1) Define and prioritize BIM data need for each FM task in each building type; 2) Identify the

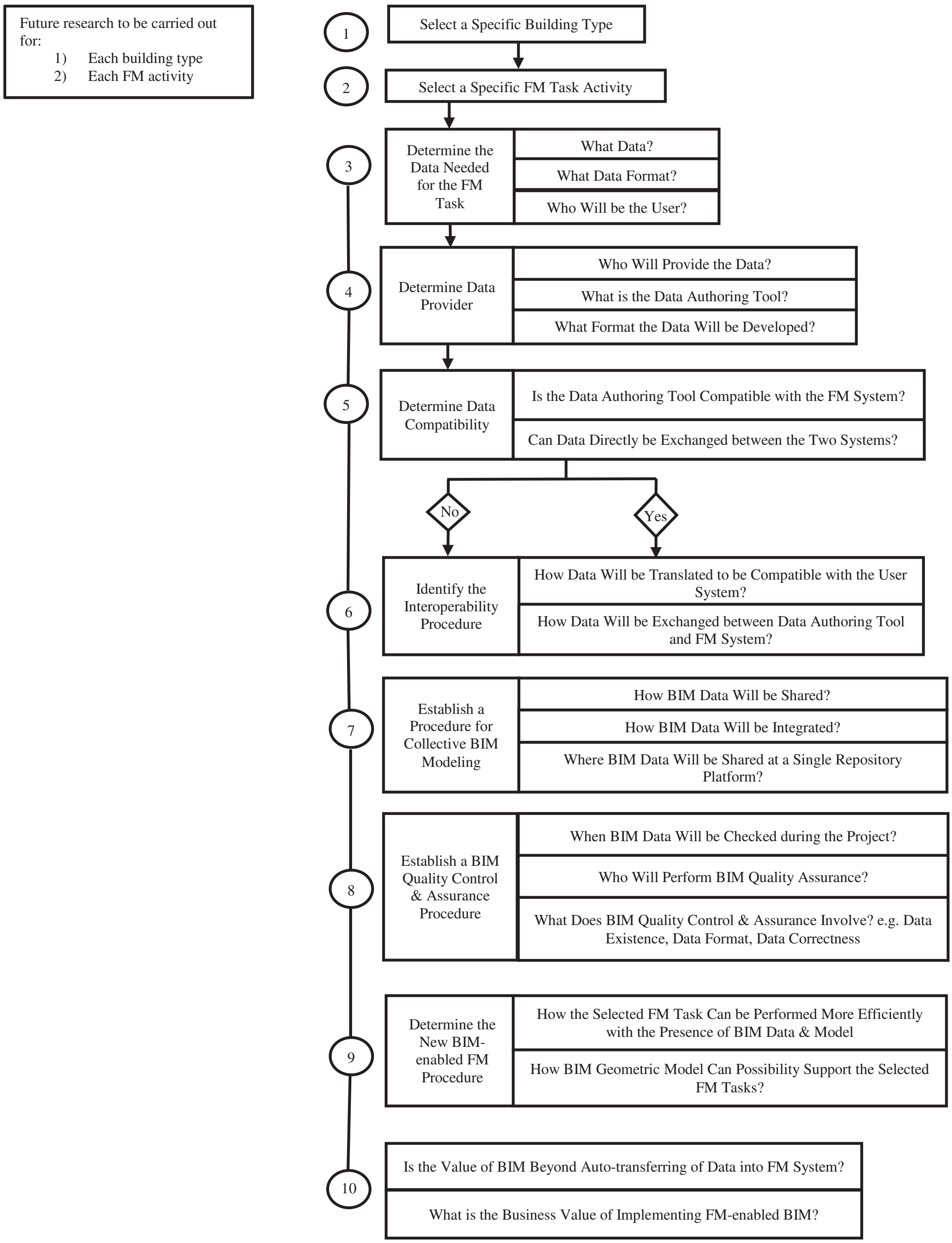


Fig. 10. A Framework for future research on FM-enabled BIM.

interoperable prominent BIM tools and FM systems and develop FM-enabled BIM workflow process for each FM task; 3) Propose a new BIM-enabled FM procedure (how FM tasks will be done more efficiently with the support of BIM data and model?); 4) Determine the business value of implementing FM-enabled BIM during project development and BIM-enable FM during operation phase. These exploratory case studies can be then followed by cross analysis of multiple case studies to establish theories and frameworks, and build the growing knowledge foundation of BIM for FM.

This research contributes to the body of knowledge by developing one of the first few exploratory pilot projects on implementation of FM-enabled BIM, as well as developing a research framework for future researchers to systematically and strategically build the knowledge foundation on BIM for FM field. The implementation process and the lessons learned captured in this pilot project and presented in this paper provide valuable insights into successful implementation of FM-enabled BIM in similar context.

We will conduct a follow-up research on this project to validate the proposed data requirements and investigate the practical applications of the as-built BIM model in supporting the facility management activities.

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