BIM-BASED LIFE CYCLE INFORMATION MANAGEMENT: INTEGRATING KNOWLEDGE OF FACILITY MANAGEMENT INTO DESIGN

By

RUI LIU

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To my family

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AECO	Architecture, Engineering, Construction and Operation
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modeling
BEP	BIM Execution Plan
bSa	The buildingSMART alliance™
bSI	The buildingSMART International
COAA	Construction Owners Association of America
COBIE	The Construction Operation Building Information Exchange
D4M	Design for Maintainability
DLL	Dynamic-link Library
EAM	Enterprise Asset Management
ERDC-CERL	The U.S. Army Engineer Research and Development Center-Construction Engineer Research Laboratory
ERP	Enterprise Resource Planning
FM	Facility Management
GFEBS	The General Fund Enterprise Business system
GSA	U.S. General Service Administration
GUI	Graphical User Interface
IAI	International Alliance for Interoperability
IFC	Industry Foundation Class
IFS	Industrial and Financial Systems
ISO	International Organization for Standardization

ITAM	Information Technology Asset Management
JVM	Java Virtual Machine
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
MEA	Maximo Enterprise Adapter
MEP	Mechanical, Electrical and Plumbing
NBIMS	National BIM Standards
NIBS	National Institute of Building Science
NIST	National Institute of Standard and Technology
ODBC	Open Database Connectivity
PIs	Performance Indicators
SAP	An ERP Software
SQL	Structured Query Language
SMC	Solibri Model Checker
SUS	State University System of Florida
XML	eXtensible Markup Language

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By

Rui Liu

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Chair: R. Raymond Issa
Co-chair: Svetlana Olbina
Major: Design, Construction and Planning

The AEC industry has raised a good deal of interest surrounding the use of BIM for facility management. The opportunities for leveraging BIM for facility operations are compelling, but the utilization of BIM in facility management is lagging behind BIM implementation in the design and construction phases. On one hand, designers and constructors seldom know what documents and other varieties of information are needed for the facility management phase. On the other hand, a limited degree of experience in the operation and maintenance knowledge of these existing buildings is fed back to the design phase. This research is aimed to bridge the communication gap between design and facility management professionals. Through available BIM extension development tools, information exchange and knowledge sharing can be attained for both these essential partners in the construction industry. The expected result would be a platform that can transfer information bi-directionally between design and facility management professionals. Through literature review, interviews and surveys with industry professionals, the requirements for facility operation and maintenance were determined. A facility management template has been developed

that carries the information needed by facility managers, as well as a predefined list for maintenance management in design tools such as Revit. Moreover, for maintainability checking, rule sets for model checker applications to gauge the accessibility of maintenance activity were created by using the Revit API and Solibri Model Checker. A relief fan case of accessibility problems was studied to illustrate and validate the Revit Add-In tool Accessibility Checker.

CHAPTER 1
INTRODUCTION

Background

Building Information Modeling (BIM) technology has undoubtedly changed the way the AEC industry executes design and construction, but will it also change the way facilities are operated and maintained (Autodesk 2008)? The AEC industry has raised a good deal of interest surrounding the use of BIM for facility management. The opportunities for leveraging BIM for facility operations are compelling, but the utilization of BIM in facility management is lagging behind the BIM implementation in design and construction phases (Akcamete et al. 2010). With the development of building information modeling, knowledge sharing between facility management and design professionals has become a more realistic possibility. BIM technology is being used in the design and construction phases. However, there is a need to expand BIM beyond the design and construction stages and to consider using BIM for the life cycle of the building, including for facility management functions such as maintenance.

Problem Statement

Kishk and Al-Hajj (1999) summarized the difficulties in the application of life cycle costing (LCC) for decision making in the AEC industry. LCC takes in a great amount of uncertainty, data imperfection, randomness and ambiguity. Probability theory and statistics in LCC can only tackle random uncertainty and cannot deal with situations such as incomplete information, human judgment, etc. The absence of sufficient and appropriate data from the historical operation phase was, and still is, a major barrier in the whole life cycle (WLC) analysis (Al-Hajj et al. 2001).

Facility managers are the ones who finally operate and maintain the designed and constructed buildings for years. There are many organizations and individual professionals in these fields. The leadership of these organizations is only now beginning to communicate and collaborate. To date, however, they have not served the facility and property managers well (Cotts et al. 2010). On one hand, as shown in Figure 1-1, designers and constructors seldom know what documents and other varieties of information are needed for the facility management phase. On the other hand, only a limited degree of experience in the use and operation knowledge of these existing buildings is sent back to the design phase for consideration (Jensen 2008). The link between design and facility management is not sufficiently understood and is usually avoided (Erdener 2003). Hence, issues related to facility maintenance have been left out of the decision-making process (Pati et al. 2010).

With the development of BIM, knowledge sharing between the facility management and design professionals has become possible. However, different stakeholders in the AEC industry are currently still working in their own silos and are afraid to cooperate with each other since inadequate interoperability is still a problem. A study by the US National Institute of Standards and Technology (NIST) showed that the annual costs were associated with inadequate interoperability among software systems was $15.8 billion (Gallaher et al. 2004). Two thirds of this cost was incurred as a result of ongoing facility operation and maintenance activities. Thus, the life cycle cost (LCC) estimation of facilities at the early design phase is inaccurate since it lacks reliable information from the operation phase.

In addition, the detailed design model is not useful for daily use by facility management. Since design software such as AutoCAD Revit, ArchiCAD etc. are for use by design professionals, requiring facility management staff to use these software packages to query the information they need is both burdensome and inefficient. Only a portion of the information from the BIM model is required. In another words, facility management staff should focus on needs and requirements, and use the available information from the BIM model. In reality, regardless of the willingness of the designer and constructor to share their models, the BIM model from the design phase cannot be used directly for facility management.

Moreover, some design defects that make maintenance activities impossible to perform are always hard to foresee in the design phase even if BIM is used and the model has been run through clash detections. Foster (2011a) noted that the largest building cost component over its life cycle is maintenance (50%), which is ignored in the design phase and proposed that the next generation of advancement for Facility Management (FM) should be in “Design for Maintenance”.

For example, current BIM software can only detect the physical conflicts between systems and components. Whether there is enough room for equipment or fittings during the maintenance phase cannot be detected automatically by the BIM clash detection tools. A non-maintenance friendly design is easy to hide in the design phase and can cause big problems in the operation phase. While there is little or no cost to correct such design defects in the design phase, it would lead to a much higher maintenance cost if the non-accessible equipment breaks down in the operation phase.

Sometimes the whole system has to be replaced because there is no way to get access to certain components during maintenance. This study focuses on (1.) the accessibility issue in the maintainability problem with the intent of accumulating a knowledge base from facility maintenance personnel about the situations that they encountered that were not accessible in the maintenance phase, and (2.) sending this information as design requirements to the design team in order to avoid future non-maintenance friendly designs. The case study in the results will illustrate this scenario.

The fact that facility management organizations fail to have standardized, centralized data repositories results in multiple servers that store information with incomplete access (East and Brodt 2007). In certain severe instances, as East and Brodt (2007) described, the data remains in the desk drawer of the people who received the disk. Scanning all the hardcopy documents and transferring them to a digital disk does not equal digital delivery. An effective and efficient system should provide the users accessibility to query and update the database.

East and Brodt (2007) confirmed in that among public agencies, at least one public owner paid three times for the construction handover information: first, the information was included in the cost of design and construction; second, the information was collected again at the end of the construction phase in a paper box; and third, since the information could not be loaded into facility management software, the owner faced additional expenditures to survey the recently erected building.

In summary, there is a knowledge and technology gap between the design and facility management professionals. Simple, approachable, and powerful integration tools are needed so that design and facility management professionals can exchange data and reduce the life cycle cost of facilities.

Research Questions

The main research question for this study is: how can design and facility management professionals efficiently share knowledge with each other? This question is broken down into the following sub-questions:

1. What information is needed from the facility management (FM) professional's point of view?
2. How can BIM help deliver this information from the designer to the FM?
3. What experiences from the FM can be beneficial for future designs?
4. How can the knowledge of FM experience be communicated as a support for future designs?

For example, the maintenance activities shown in the BIM model can be used to find the root cause of each problem, and thus generate a better design for a future project.

Aim and Objectives of Study

The aim of this research is to bridge the communication gap between design and facility management professionals. Through available BIM extension development tools, information exchange and knowledge sharing can be attained for both these essential partners in the construction industry. The expected result would be a platform that can transfer information bi-directionally between design and facility management professionals, i.e. the new platform can send operation and maintenance information back to the design professional, and use the BIM model to assist facility management.

The first objective of the research is to investigate the requirements of facility management that need to be addressed in the design phase.

The second objective is to examine possible BIM solutions and tools for these facility management requirements.

The third objective is to develop and test a communication platform between BIM design software and the requirements of facility management. A platform is then built that can use the BIM model from the design phase to perform facility management.

The fourth objective is to validate the platforms developed between BIM design applications and facility management applications.

Contribution and Significance

The AEC industry is shifting to a new business paradigm, and BIM is at the center of this shift. As new information technology emerges and is updated on a daily basis, the expectations and requirements from AEC practitioners on building projects increase simultaneously. The fundamental contribution of this research is to bridge the knowledge and technology gap between design and facility management professionals. A Revit Add-In Accessibility Checker was developed to access accessibility problems of objects in the design phase, which can facilitate the designer and engineer to relocate the objects to a location that is easier to access for facility maintenance work. A platform was built that can help deliver information from the design and construction phases to the facility management phase to promote communication between the design phase and the FM phase without repetitive work on information collection. To reduce the life cycle cost of facilities, simple, easy to use, and powerful integration tools are needed so that design and facility management professionals can share their knowledge and exchange data.

A comprehensive literature review was conducted to explore the theoretical foundation of facility management, the requirements of FM, and their valuable experiential knowledge which can be integrated into the design phase. Existing knowledge in this area is still in a conceptual phase. Researchers note that FM knowledge is important for design, and an integrated environment is crucial for both design and FM (Bröchner 2003, Jensen 2008). However, how are design and FM integrated? What knowledge is deemed valuable? Such questions have yet to be answered and are addressed by this research.

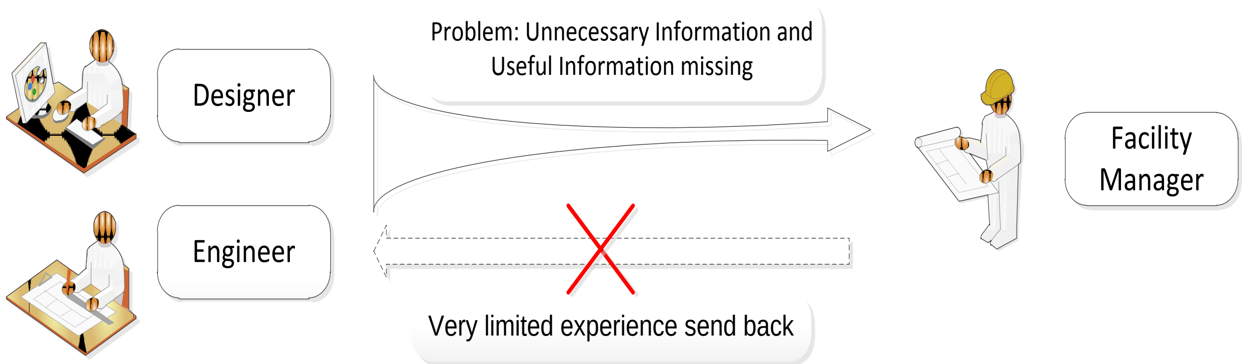

Figure 1-1. Communication problems between Architect/Enginner and Facility Manager

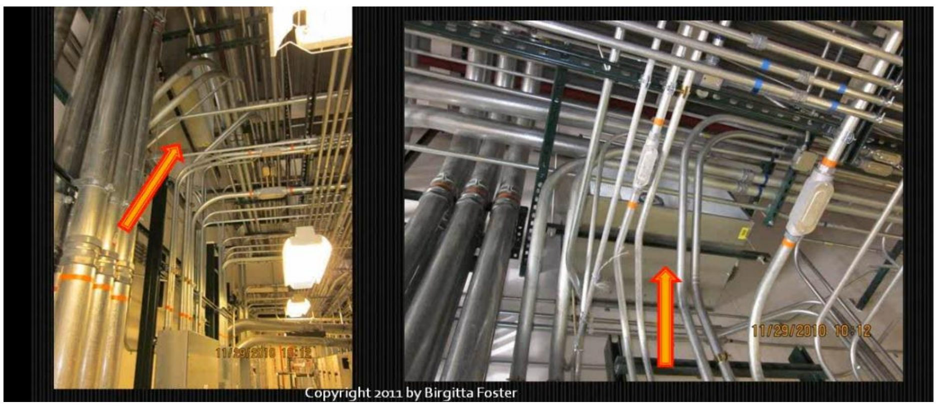

Figure 1-2. Relief fan example (Source: Foster 2011a)

CHAPTER 2
LITERATURE REVIEW

Overview

This chapter reviews literature related to the research efforts and trends in BIM and FM integration, and covers the development of BIM concepts and BIM applications and related research on integrated Facility Management, and Design for Maintainability.

Building Information Modeling (BIM)

In recent years, Building information Modeling (BIM) has received much attention from both academia and the construction industry. Considered the future of this industry, BIM introduces many opportunities for the improvement of business information transfer throughout the construction process (Liu et al. 2010). However, BIM as a technology is not new to the AECO industry. It has been developed under different names such as building product model, virtual building and intelligent object model for over 20 years. These concepts can be perceived as the earlier phases of BIM (Wu 2010).

Howard (1998) foreshadowed the lack of success encountered by BIM by stating, "as the number of available CAD packages grew in the late 1970s and 1980s, the early ambitions for complete 3-D modeling and automated design were put aside and drawing production became the most realistic goal of architectural, and later, engineering consultants." The AEC industry has generated much curiosity around the use of BIM for facility management. The opportunities for leveraging BIM for facility operations are compelling, but utilization of BIMs in facility management is falling behind the BIM implementation in design and construction phases (Akcamete et al. 2010).

Definition of BIM

Development of BIM concept

The earliest BIM concept was published by Eastman (1975). After more than three decades of development, it appears to be one of the most promising developments in the AEC industry.

Eastman (2008) defines BIM as a modeling technology and associated set of processes to produce, communicate, and analyze building models. The Associated General Contractors (AGC) defines BIM as “the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users’ needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility” (AGC 2006).

The Project Committee of National Building Information Standard (NIBS), one of the leading organizations that conduct BIM research, defines BIM as follows:

> A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward. A basic premise of BIM is collaboration by different stakeholders at different phases of the lifecycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder. The BIM is a shared digital representation founded on open standards for interoperability (NBIMS 2007, 2012).

Based on this definition, the essence of BIM includes the digital representation of projects and a shared life cycle knowledge information database in order to support decision making at different stages of projects by project stakeholders. In addition, BIM should have open standards for interoperability that can support information exchange across different formats and platforms.

A survey conducted by Suermann (2008) found that industry has not yet reached a consensual definition for BIM. Some identify BIM as means of 3D modeling and visualization only. Smith (2008) proposed a more useful concept: a Model should access all pertinent graphic and non-graphic information about a facility as an integrated resource. A primary goal is to eliminate the re-gathering or reformatting of facility information, which is a wasteful practice.

n-Dimension of BIM

As discussed above, BIM is not merely a Three Dimensional Model. A real building information model should hold information for different stakeholders at different phases of the facility's life cycle. The need for information that can be inserted, extracted, updated, or modified, is apparent on all levels of interest.

Based on the different varieties of information encompassed by a BIM model, researchers and industry practitioners categorize it as an n-Dimensional BIM, such as 3D, 4D, 5D, and 6D BIM. 3D always refers to the three spatial dimensions of the building model, namely, the width, length and height. The scope of BIM extends beyond 3D to 4D, where the aspect of time is added to form schedules; and to 5D, where the cost component helps create estimates. The 6D aspect, with project controls and life cycle management, is presently being developed (Luthra 2010). Some researchers (Qi et al. 2011, Zhang et al. 2012) also add the 7th dimension, such as integrating design for safety, based on OSHA regulations, into the BIM model. Regardless of what dimensions the BIM model may assume, all these aspects are simply efforts to apply more information and knowledge to the model, and thus improve integration and coordination in the AEC industry. However, the facility management phase, especially facility maintainability, has yet to be addressed in current BIM dimensions.

BIM Application and Research

BIM software can be classified into several disciplines, such as architecture, structural engineering, mechanical, electrical and plumbing (MEP), construction, planning and visualization, codes and specifications, and facility and asset management. These disciplines are clearly shown by a BIM software roadmap depicting the classification of current BIM software. Figure 2-1, developed by the Quarry Group, shows the various software applications divided into different disciplines. It also illustrates how data can be transferred between different software applications (Quarry Group 2009). Current commercial BIM software platforms, featuring their company and product information, are listed in Table 2-1.

BIM Benefits

As shown in Figure 2-2, the life cycle cost of a typical design/build approach with required maintenance conducted over time is shown in light orange. The life cycle cost of a typical project that fails to do preventative maintenance is shown by the dark orange line, which is a classic life cycle cost curve in most projects, because the project owners usually lower the maintenance budget cost of the beginning phase of the project in order to show a higher return on investment for resale purposes. However, since no preventative maintenance was conducted at the beginning of the life cycle, the later reactive maintenance activities will cost more than anticipated. As BIM technology has currently been implemented mostly in the design and construction phase, the faster delivery and fewer change orders on BIM projects yield the savings shown in the blue area. This study, however, does not mention the investment in the red question mark area, as with BIM adoption, there is more investment in the early design phase, so the total savings in design and construction phase should be the blue area minus the red area. In addition, based on this study, the untapped savings in the O&M and closure stages are in the green area, which can yield much more savings if BIM can be used through the life cycle of the building. Because of these potential savings, represented by the green area, this research is focused on life cycle use of the BIM model that can help achieve the savings represented by the green area.

BIM Challenges

As successful implementation of BIM requires different parties in the construction industry to share their BIM model, the ownership of BIM data and how to determine and protect the ownership through laws and contracts becomes the first legal risk for BIM implementation. For instance, the owners may feel that they should own the design as the owner pays for the design, but since the team members are providing proprietary information for use, the proprietary information needs to also be protected. As a result, there is no simple answer to the data ownership question (Azhar et al. 2008). In addition, when project team members contribute data that can be integrated into the BIM model, such as material vendors or equipment suppliers, licensing issues may also arise (Thomson and Miner 2006). The responsibility for updating BIM data and making sure it is accurate is another challenge for BIM implementation. More time is required for inputting BIM data and reviewing BIM data which add more cost to the design and administration process. As a result, not only must the risks of BIM be identified and allocated, but also the cost of BIM implementation has to be put into the budget before BIM can be fully utilized (Thomson and Miner 2006).

In order to effectively implement the use of information, the project data must be able to be represented in a common interpretable form, which allows for an accurate exchange of data among different computer systems and platforms (Pniewski 2011). This issue of interoperability is one of the main challenges that BIM has faced since its inception. BIM software programs have been “evolving in pursuit of different solutions” in competition with one another which makes it difficult to fully implement all the desired capabilities within one program or software platform. Moreover, when project data are submitted by different parties in different formats incompatible with the software, additional time is required by project/VDC managers to re-submit data. The question therefore arises whether initial deployment of BIM may actually obstruct productivity (Thomson and Miner 2006). To improve these issues the first national BIM standard (NBIM) was released by The National Institute of Building Sciences’ (NIBS) Facility Information Council (FIC) to facilitate standardization of the process from design schematics to life cycle process (Consulting Specifying Engineer 2008). While the productivity and economic benefits of BIM to the AEC industry have been widely acknowledged and increasingly well understood, and the technology of BIM is readily available and rapidly growing, BIM adoption seems to be much slower than anticipated (Fischer and Kunz 2004). Technical and managerial issues are the two main reasons for the slow adoption rate.

The technical reasons can be classified into three categories generally (Bernstein and Pittman 2004):

- the need for well-defined transactional construction process models to eliminate data interoperability issues,
- the requirements that digital design data be computable, and
- the need for well-developed practical strategies for the purposeful exchange and integration of meaningful information among the BIM model components.

The primary management issue concerning the use of BIM is that currently there is no clear consensus about how to implement or use BIM. Some software companies are making money on the “buzz” of BIM, and developing programs to address some quantitative aspects of it, but they do not treat the process as a whole. There is a need to standardize the BIM process and to define the guidelines for BIM implementation (Azhar et al. 2008). Moreover, in past practice, facilities managers (FM) have seldom been included in the early building planning process, thus maintenance strategies, based on the as-built condition, were implemented when the owner takes possession of the building. BIM may offer facilities managers a chance to enter the picture at a much earlier stage in the future, giving them more influence on the design and construction process. The nature of the BIM allows all the different stakeholders to supply corresponding information to the building manager before the building is even completed. Finding the right time to include these people in the process will undeniably be a great challenge for owners (Azhar et al. 2008).

Integration Facility Management

Facilities operations and maintenance includes all aspects of services required to ensure that the constructed environment will reach the performance criteria for which it was designed. Simply put, operations and maintenance constitute the everyday activities necessary for the building and its systems and equipment to perform their intended functions (Sapp 2009). Cost increases in maintenance can be a result of deficiency in design (Al-Hammad et al. 1997). A survey of building failure patterns and their implications, conducted by the Building Research Establishment in England, found that 58 percent of the defects were caused by faulty design (Seeley 1995). Ishak et al. (2007) highlighted the effects of faulty design on building maintenance. They claim that these faults set a heavy burden on the building for the rest of its life, and are without remedial compensation. The responsibility falls on the shoulders of the designer, who is, however, always immune from any of his design faults once the building has been erected. They do not receive any feedback from either building users or facility managers about the integrity of their buildings until an accident happens. "Architects in the United States have historically been bound by comprehensive legal requirements and responsibilities for the building design. They are legally obligated to safeguard the public health, safety, and welfare (Gabrielli 2010)." Today, as buildings are designed to meet higher standards than in the past, the influence of design on the operation and maintenance of buildings is greater than ever before. The effects of these decisions made during the design stage would have far reaching effects on future maintainability (Chew et al. 2004)."

Erdener (2003) proposed the potential of programming as a link between design and FM, but did not provide a role for the facility manager in the integrated design environment. Mohammed and Hassanain (2010) illustrated the role of a facility management team in the integrated design team. As shown in Figure 2-3, the facility management team acts as a manager involved in the whole process of the project, which is, to some extent, impossible in most cases. First of all, since the facility management team's main function is to operate and maintain existing buildings, they may lack the amount of time needed for a new building. Second, in the design phase, the facility management team may not have been appointed yet or is not yet available. Therefore, this model cannot practically include the facility management team in all aspects of the new building's establishment.

Bröchner (2003) attempted to investigate avenues toward integrating facility design and service, assuming that economic efficiency is the ultimate goal in the facility owner's view. He compared the construction industry with manufacturing. Manufacturers have numerous sources to integrate customer requirements in the design of products, while at least half of these resources are nonexistent in the construction design context. The responsibility falls on the facilities' managers, as sources of customer requirements to provide this information. Bröchner concluded that the integrated development of design and services for facilities is still a distant reality.

A US National Institute of Standards and Technology (NIST) study has shown that the annual cost associated with inadequate interoperability among software systems was $15.8 billion (Gallaher 2004). Two-thirds of this expense is a result of ongoing facility operation and maintenance activities (Shen et al. 2010). Fiatech (2009) found some major problems related to system interoperability in the construction industry. The problems discovered by their research are as follows:

- Program plans and designs are optimized for a limited set of parameters in a limited domain. The capability to support "total best value" decisions does not exist.
- Life cycle issues are not well understood and therefore modeling and planning do not effectively take all life cycle aspects into account.

- Operation, maintenance, environmental impact, and end-of-life disposal issues are given limited consideration in the project planning equation.

It is necessary to expand this domain by considering other parameters in the design phase, especially input from the end user's facility manager's experience.

BIM for Operations and Maintenance

The operation phase constitutes approximately 60% of the total cost of a construction project. The main activities during facility operations are related to maintenance and repair (M&R). Reactive maintenance and repairs create excessive expenses, but it must be remembered that most maintenance work is reactive (Akcamete et al. 2010, Mobley et al. 2008, Sullivan et al. 2010). Since reactive maintenance cost three to four times more than the planned maintenance for the same repair, the current approach is not efficient (Mobley et al. 2008, Sullivan et al. 2010). So it is reasonable to support more planned maintenance work and not just reacting to failures. Sullivan (2010) recommended prioritizing the components in a facility, recording root causes of failures and analyzing equipment failure modes in order to capture reliable information for reactive maintenance. A reliable maintenance database, holding historical information of maintenance and repair (M&R) work, is necessary for planned maintenance decisions. Since significant unnecessary expenses occur in the current practice, there are ample opportunities for major savings in the operation phases. Thus, computerized support is needed for the improvement of operation and maintenance activities (Akcamete et al. 2010).

An effective CMMS system should include the various aspects of maintenance management functions. This ideally consists of work order management, preventive maintenance management, inventory management, equipment management, procurement management, external contractors and internal staff resources management, workflow management, etc (2009).

In the construction industry, FM: Systems and Autodesk have released an interactive workplace management suite which offers the following benefits including space management, asset management, facility maintenance management (FM: Systems 2010). Sandia National Laboratories has made an effort to find a solution to the interoperability issue facing Maximo, a facility management software, and Revit (Liu 2010).

Facility Management Feedback to Design

Knowledge transfer from building maintenance and operation to building design is not a new idea. Bröchner (1996) mentioned relevant experiments from Sweden in the 1960's, but the results were far from satisfactory. With the development of information technology, Bröchner expected that this knowledge transfer should become easier. He focused his study on a particular building and dispatched the feedback from operation to the design team that was responsible for this building. Jensen (2008) proposed to obtain feedback from the operation phase to the design of new buildings. His research also considered the lessons to be learned from both the operations of existing buildings and newly designed buildings. In Denmark, during the 1980's, operational friendly buildings were the subject of increased research interests, resulting in the recommendations for different project parties about what activities should be allocated for each phase. A number of tools to support the activities were developed. Nonetheless, this research has had little impact on Danish industrial practices (Jensen 2008).

The British Institute of Facilities Management (BIFM) commissioned a project to the BRE (Building Research Establishment), which was aimed at bringing facilities' expertise into the design process. They produced a report that analyzed why and when facilities management should be involved in the design phase, and why, in reality, they were not involved (Jaunzens et al. 2001). One of the main problems discussed was the fact that facilities managers are not sufficiently qualified and are not accepted as an equal dialogue partner in the design phase. In order to change the current status, which ignores facilities management in the design phase, their potential knowledge in the matter should be considered. Their insight could be vital to the design professionals.

Facility maintenance indicators have been investigated in view of bridging the divide between facility design and facility maintenance activities (Pati et al. 2010). Two sets of facility maintenance indicators can be developed for consideration during strategic decision making process including sets of hard and soft facility maintenance performance indicators (PIs). The set of "hard" indicators, developed as a part of the funded research by U.S. GSA, includes objective indicators for maintenance policy justification and budget allocation. The hard PIs discussed in the study by Pati et al. (2010) are building performance index (BPI), manpower sources diagram (MSD), maintenance efficiency index (MEI), managerial span of control (MSC), business availability (BA), manpower utilization index (MUI), urgent repair request index (URI), preventative maintenance ratio (PMR), and maintenance productivity (MP). The set of "soft" indicators, developed based on theories and models in the multidisciplinary area of environment and behavior, includes near visual task (NVT), far visual task (FVT), speech comprehension indicator (SCI) and many others for the courtroom example, different types of buildings should develop different PIs. Building users rated the degree of functions based on as-built description and evaluative data. Principle components analysis and multivariate regression models were developed to investigate the association between as-built physical factors and the performance dimensions. Examples of hospital, courthouse and office building design were used to articulate how facility maintenance indicators can be developed and support organizational strategic decision making. The study showed how the two sets PIs are designed to address different scales of decision making (Pati et al. 2010).

BIM Execution Plan (BEP)

The BIM Execution Plan is intended to be used as a guideline offered by owners to other parties such as designers, constructors, subcontractors, and manufactures with a detailed process for executing BIM on their project. Different organizations may have different names for such a plan even though it serves the same purpose. For example, the GSA called their execution plan the GSA BIM Guide. It defines uses for BIM on the projects (e.g. design authoring, design reviews, 3D coordination, and record modeling), along with a detailed process for executing BIM on each project. Some of the BIM execution plans have some items about maintenance and maintainability issues. Table 2-2 lists the corresponding maintenance related items for each of the BIM execution plans studied.

A good BIM execution plan should serve as a guideline that makes clear the owners' requirement of BIM and offers the designers, constructors and other parties a clear list of what they need to deliver to the owner at different phases of the project. But the current BEPs published by different organizations are still generic and do not give clear descriptions of specific requirements of the owners. For example, GSA and PSU focus on the life cycle data transfer and delivery from design, construction to the facility operation and maintenance phase, but not on maintainability issues such as MEP equipment clearance zones and personnel access. UF and VA both have some items about MEP clearance for maintenance purposes, but the description is rather generic, from the execution plan itself, there is no definition about how to measure such clearance to satisfy maintainability. Indiana University only has items about information delivery to the O&M phase but not maintenance clearance issues.

Interoperability between Design Platforms and CMMS

Construction operations building information exchange (COBie)

Documents including equipment lists, product data sheets, warranties, spare part lists, preventive maintenance schedules, and other information are required through the contracts to support the operation and maintenance of facilities by property owners. Current industry practice is to gather such information at the end of the construction job, which is expensive because most of the information has to be regenerated even if it has been generated earlier (East 2012). The COBie specification is to capture the data as it is created for the first time during design and construction and provide it to the facility operation group (Nisbet 2008).

COBie simplifies the work process to capture and record project data. As shown in Figure 2-4, designers provide information about floor, space, and equipment layouts. Contractors provide product data, as-built layout, and the serial numbers of installed equipment. Data provided by contractors are offered directly by product manufacturers who can also participate in COBie. The COBie Standard was developed based on the Industry Foundation Class (IFC) model. To facilitate the use of the COBie standard for maintenance and renovation projects, the data import and export from CMMS is required (Nisbet 2008).

COBie interoperability with MAXIMO

The U.S. Army Engineer Research and Development Center-Construction Engineer Research Laboratory (ERDC-CERL), cooperated with buildingSmart alliance, developed the COBie information exchange standard to help electronic transfer of construction documents and information to facility owners. There are two ways to make the connection between COBie and CMMS. One way is to access the underlying proprietary database. This method offers substantial flexibility but can only access and update one table at a time. The other way is to use the provided business-object interfaces, which may cause some loss of flexibility but can offer comprehensive security and transaction management, automatic validation of data, detailed logs, and updates to multiple tables (Nisbet 2008).

Task 1 in the map is to transfer data from ifcXML to Maximo CMMS through maximoXML and Maximo Enterprise Adapter (MEA). Task 2 is to transfer data from CMMS Maximo back to ifcXML through operators with Adobe Forms as shown in Figure 2-5.

IFS and GFEBS are Enterprise Asset Management (EAM) systems that can offer the same CMMS functions as Maximo. The future work of buildingSMART alliance is to make the data workflow work for other systems such as IFS and GFEBS (Nisbet 2008).

Design for Maintainability (D4M)

Arditi and Nawakorawi (1999a, 1999b) claimed that 50% of the maintenance related problems can be eliminated if design defects can be prevented during the design phase. When considered in the early design phase when flexibility is high and design change cost is low, product maintainability can eliminate maintenance costs, reduce downtime and improve safety (FitzGerald 2011). The operation phase constitutes approximately 60% of the total cost of a construction project. The main activities during operations are related to maintenance and repair (M&R). Reactive maintenance and repairs bring excessive expenses. However, the nature of most maintenance work tends to be non-routine and reactive (Akcamete et al. 2010, Mobley et al. 2008). Reactive maintenance and repairs are not efficient, since they cost three to four times more than the planned maintenance for the same repair (Sullivan et al. 2010, Mobley et al. 2008). So it is reasonable to support more planned maintenance work instead of just reacting to failures. Sullivan et al. (2010) recommended among others prioritizing the components in a facility, recording root causes of failures and analyzing equipment failure modes in order to capture reliable information. A reliable maintenance database containing historical information of M&R work is necessary for planned maintenance decisions. Since significant unnecessary expenses occur in current practice, there are ample opportunities for major savings in the operation phase and computerized tools are needed for the improvement of operation and maintenance activities (Akcamete et al. 2010).

An effective Computerized Maintenance Management System (CMMS) should include the various aspects of maintenance management functions. These systems ideally include work order management, preventive maintenance management, inventory management, equipment management, procurement management, external contractors and internal staff resources management, workflow management, etc. (RFP Magazine 2009). In the construction industry, FM:Systems and Autodesk have released an interactive workplace management suite that can provide information about building mechanical equipment for preventative maintenance that is derived from the BIM model (FM:Systems 2010). Although the development of this suite is a good effort to connect BIM and FM, this platform does not consider the maintenance requirements in the design phase.

Maintenance management and energy consumption are two key areas of concern for facility managers (Lewis et al. 2011). While energy management is undergoing comprehensive studies, maintenance management is far under-researched even though it constitutes a large part of the life cycle cost of a building project (Foster 2011a). Through three case studies on California facilities, Lewis proposed that energy consumption has an interdependent link with maintenance management. Proper maintenance is necessary to achieve optimal energy performance (Lewis et al. 2011). Akcamete (2010) proposed the use of 3D BIM visualization capabilities to represent the spatial relationship of work orders to support more effective maintenance planning. In addition, most of the maintenance problems are not attributed to construction problems, but are due to design defects. If the facility manager's involvement can be brought into the design phase, major repairs and alterations in the lifespan of the facility will be reduced (Mohammed 2010). It is difficult, however, to get the facility manager involved early on in the design phase because during the design phase, the facility management team may not have been set up yet. Thus bringing the facility management team's knowledge through BIM software, which does not require the physical presence of the facility management staff, can be a solution to this problem.

Summary

BIM and its ability to collect and provide modeling and proprietary data throughout the life cycle of a construction project theoretically make the delivery of required accurate information possible for the AECO industry. Some researchers have noted that problems, such as the communication gaps between the design, construction and facility operation phases, exist. However, currently, practitioners and researchers are still focusing on the implementation of BIM in the design and construction phases, and few efforts have been put into the facility management phase, which constitutes a more significant part of the life cycle cost of a construction project. Research efforts are required to study the communication between the design, construction phases and the facility management phase to bridge the gap between these two ends of the project.

Table 2-1. Current BIM software platform (Adapted from: Holness 2010)

	Current Commercial Application Software		
	Organization	Product	Browser Address
Current Modeling Software	Bentley Systems	Microstation – Architecture, Structural, Civil, MEP.	www.bentley.com
	Bentley Solutions	AutoPIPE, HVAC & Facilities Tri Forma, Factory CAD	
	Autodesk	AutoCAD– Architecture, Structural, MEP Revit	www.autodesk.com www.autoCAD.com
	Graphisoft	ArchiCAD 11 Virtual Building Solutions	www.graphisoft.com
	Oracle	Building Information Management Platform CBIM	www.oracle.com/global/uk/pressroom/2006/613.html
	Granlund	RIUSKA Integrated Building Solutions	www.granlund.fi/intro.html
Current Viewing Management Software	Navisworks	Jetstream 3D (open protocol management)	www.navisworks.com
	Nemetschek	Integrated IT Solutions All Plan IFC Viewer	www.nemetschek.com
	Newforma	Project Viewing and Management	www.newforma.com
	Solibri	IFC Optimizer – Data Storage and Transmission	www.solibri.com
	Mayo Clinic	Mayo Graphical Integrated Computer Aided Design MagiCAD	www.magicad.co.uk/
Current Model Checking and Code Compliance Software	Solibri	IFC Optimizer & Model Checker	www.solibri.com
	CORENET	ePlan and Fornax Viewer	www.corenet.ess.gov.sg/ www.aecbytes.com
	AEC3 UK	XABIO & Octaga Player	www.aec3.com
	DOE	COMcheck	www.doe.gov www.eere.energy.gov/buildings/tools_directory/
	Australia, CRC for CI	EDM	(Greenwood et al. 2010)
Current Related Construction Management Software	Bentley	Project Wise	www.bentley.com
	E-Builder	Web Based Project Management	www.e-builder.net
	Primavera	Project Management	www.primavera.com
	Autodesk	Buzzsaw	www.autodesk.com
Current Facility Management Software/System	FM: Systems	FM: Interact V8	www.fmsystems.com
	EcoDomus	EcoDomus FM	www.ecodomus.com
	Autodesk	FMDesktop	www.autodesk.com (Discontinued)

Table 2-2. Maintenance related items in BIM execution plans

Name	Organization	Related items to maintenance and maintainability
BIM Execution Plan: Guidelines and Standards (Version 1.1)	University of Florida (2012)	• Establish protocols for all contractor/sub-contractor modeling including verification of "work zones" for allocation of overhead MEP/FP space • Include generic mass in model for equipment clearances and access zones for MEP/FP equipment and accessories requiring access by maintenance personnel. (Note: design models may contain these elements to some extent. However, this should be comprehensively reviewed and accounted for during the jobsite coordination process. • Collision report specifically depicting all generic mass modeled clearance zones for MEP/FP equipment and accessories requiring maintenance personnel access. All irresolvable clash detections within these zones shall be discussed with UF and design team representatives for resolution prior to designating this section of coordination review cleared for shop drawings and fabrication.
GSA Building information Modeling Guide Series: *08-GSA BIM Guide for Facility Management*	U.S. General Services Administration (GSA) (2011)	• Executive summary: Facility data is created throughout the design and construction process. GSA intends to use and update this data throughout the facility life cycle – through Small Projects, Operations & Maintenance, and Major Renovations & Alterations. • 1.3 The data requirement to support GSA business needs-equipment information-ID, make, model, serial number, warranty information, maintenance instruction, etc. • 1.3.2.2 Populating BIM data into CMMS at project turnover • 3.2.2 GSA is currently developing a National Equipment Standard to be used on GSA projects in order to enable GSA to leverage equipment data through the facility life cycle. GSA intends to utilize and update this data throughout the facility life cycle.

Table 2-2. Continued

Name	Organization	Related items to maintenance and maintainability
The VA BIM Guide	Department of Veterans Affairs (2010)	• 3.1d, 3.2 e Animations/graphics showing major building equipment and medical equipment space clearance reservations for operations, repair, maintenance, replacement. • 4.3 Off-Site Fabrication Formulate with BIM Mgr. and designer. Map BIM use for fabrication and shop drawing design. Determine BIM use for simulations of maintenance space analysis, and documentation. Identify tools. • 7.4 During design, special consideration must be given to medical staff and maintenance issues. Animations/graphics showing major building equipment and medical equipment space clearance reservations for operations, repair, maintenance, replacement • 7.9b Provide adequate space for construction and maintenance access to structural elements, building equipment, and distribution systems. Clearance reservations for equipment maintenance filter removal, and equipment removal and replacement shall be modeled with the equipment, and sign-off on the adequacy of the space reservations shall be obtained from the facility Chief Engineer. • 8.1b Clearance reservations for equipment maintenance filter removal, and equipment removal and replacement shall be modeled with the equipment, and sign-off on the adequacy of the space reservations shall be obtained from the facility Chief Engineer.
Architectural Design Manual	Department of Veterans Affairs: Office of Construction & Facilities Management (2011)	• 1.4 The A/E shall ensure the design supports quality based performance measures for customer satisfaction, energy consumption, and reduced operations and maintenance. • 2.4.10 The essential criteria for selection of products/materials is based on their appropriateness for function and space, sustainability, life cycle costs, durability, and ease of maintenance.

Table 2-2. Continued

Name	Organization	Related items to maintenance and maintainability
Architectural Design Manual (cont.)		• 4.6.6 MAINTENANCE-SHOP ENTRANCE PLATFORMS Entrance platforms to maintenance shop floors shall be 150 mm (6 in.) high above grade, at same level as shop floors, and shall be a minimum of 3 m (10 ft.) wide. Slope platform away from the building. Provide double doors at platforms to permit direct transfer of long lengths of pipe, lumber, etc. to maintenance shop storage areas. • 4.9.1 Provide door-operator controls and equipment that are easily accessible for maintenance. • 4.13.3 Provide roof walkways of prefabricated asphalt planks with non-slip surfaces on access routes over roofs to mechanical equipment requiring recurrent maintenance.
BIM Execution Planning Guide	The Pennsylvania State University (2010)	• Appendix B Building (Preventative) Maintenance Scheduling Design review software to view Record Model and components. Computerized Maintenance Management System (CMMS) linked to Record Model. • Appendix B Space Management and Tracking A process in which BIM is utilized to effectively allocate, manage, and track assigned workspaces and related resources. A BIM model will allow the facility management team to analyze the existing use of the space and appropriately manage changes in clientele, use of space, and future changes throughout the facility's life. Space management and tracking is an application of the record model.

Table 2-2. Continued

Name	Organization	Related items to maintenance and maintainability
BIM Execution Planning Guide (cont.)		• Appendix K Record Modeling • The record model should, as a minimum, contain information relating to the main architectural and MEP elements. Additional information including equipment and space planning systems may be necessary if the owner intends to utilize the information. Furthermore, with the continuous updating and improvement of the record model and the capability to store more information, the model contains a true depiction of space with a link to information such as serial codes, warranties and maintenance history of all the components in the building.
BIM Execution Planning Guide	Indiana University (2009)	• 3.7.3 O&M (Operations & Maintenance) Manuals The contractor shall submit the following information to Indiana University – two paper copies in binders of the O&M Manuals along with the Construction Operations Building Information Exchange (COBIE) format: (1) the make, model and serial number of each piece of installed equipment, (2) the location of any equipment installed in the building, and (3) manufacturer's documents including cut sheets, installation instructions, and recommend maintenance tasks, testing or other reports. An electronic format of the O&M manuals shall also be submitted along with the paper copies, the format shall be color PDF and native Excel files.

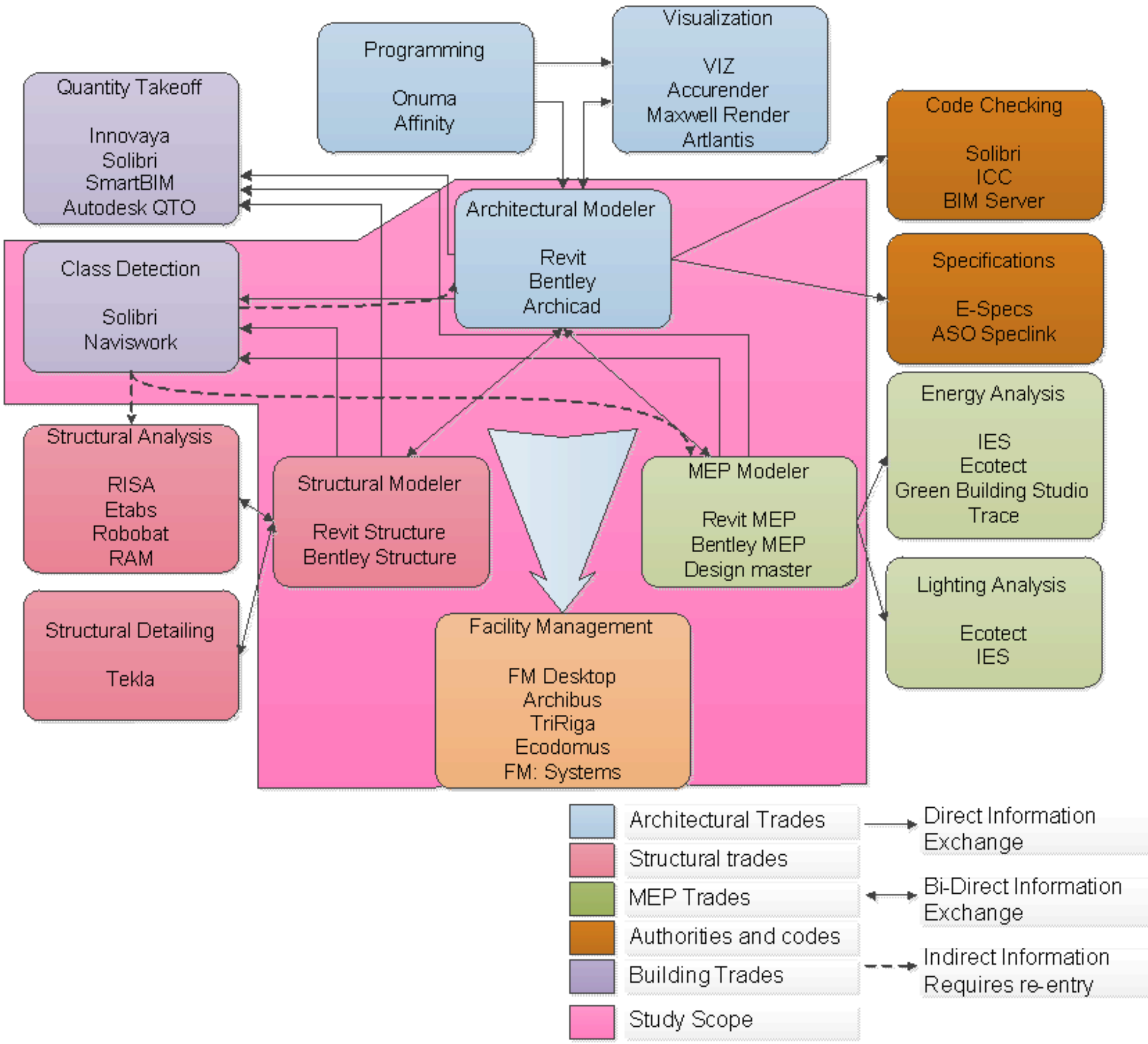

Figure 2-1. BIM roadmap defined by software (Adapted from Quarry BIM Road Map: Thompson 2008)

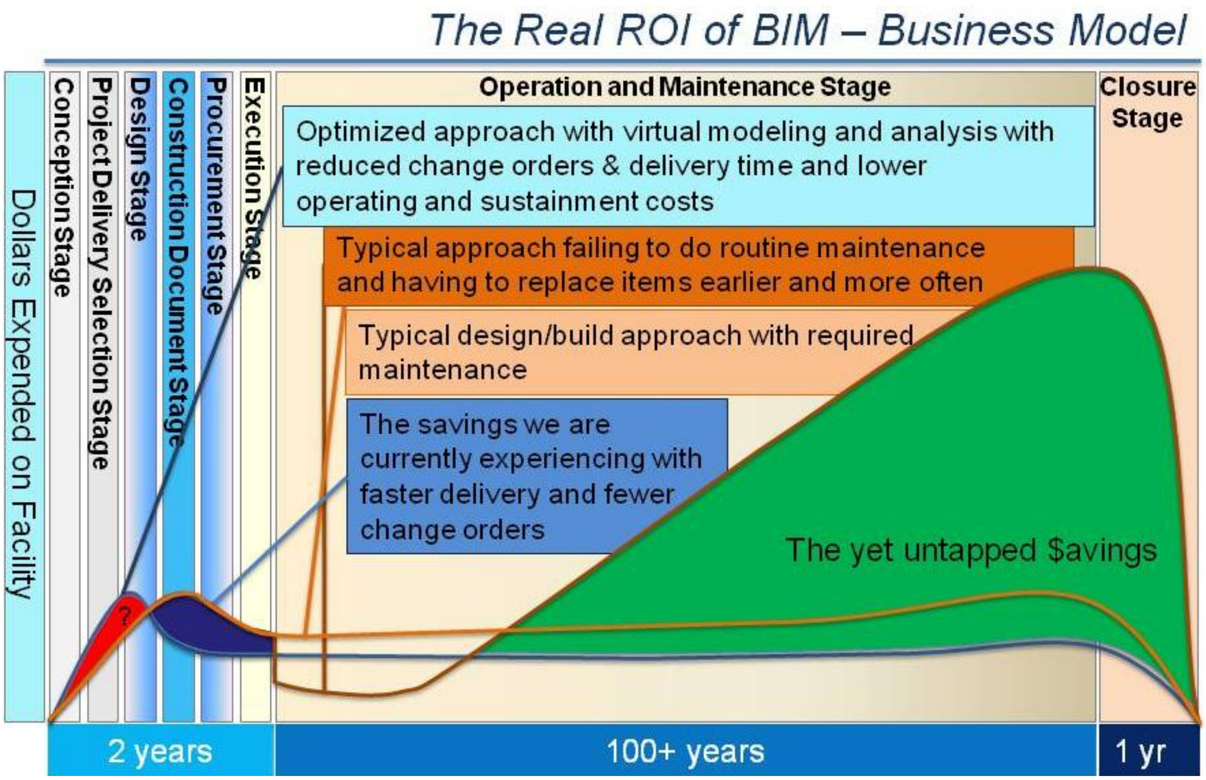

Figure 2-2. Real ROI of BIM-Business Model (Adapted from: Grobler 2011)

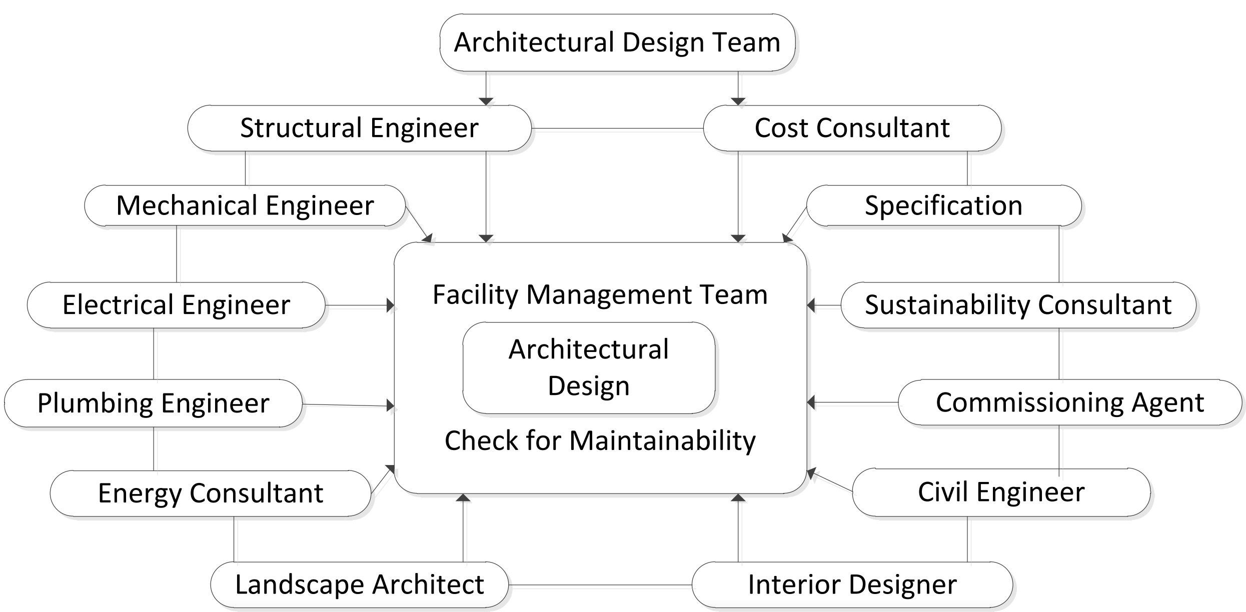

Figure 2-3. Role of the facility management team within the integrated design team (Adapted from: Mohammed and Hassanain 2010)

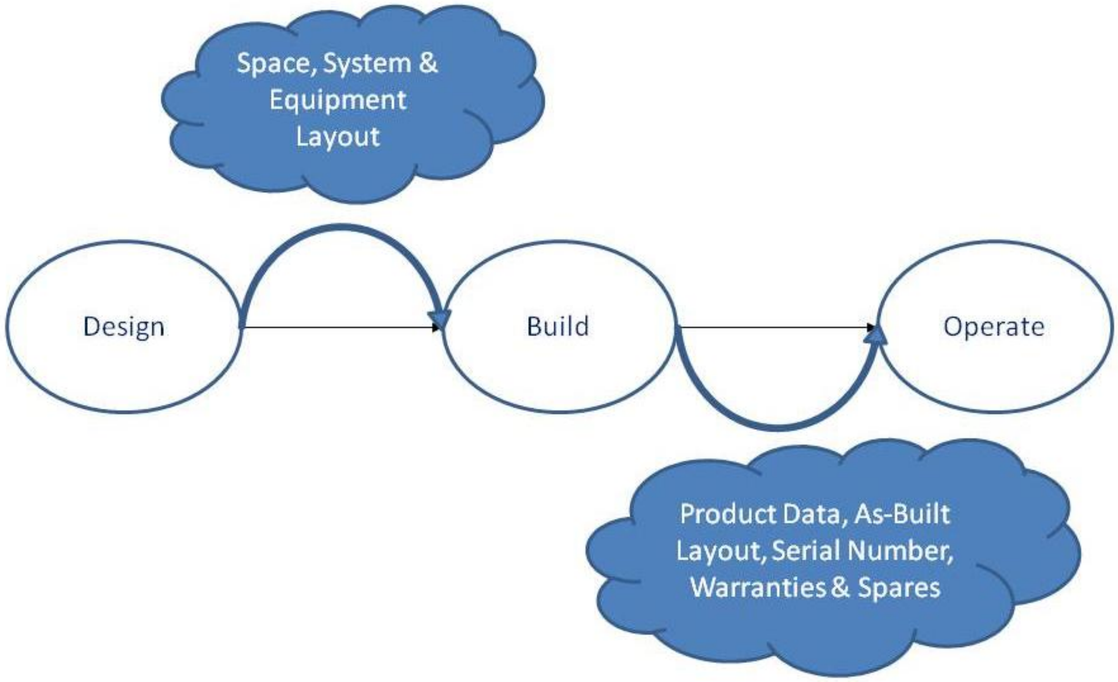

Figure 2-4. COBie process overview (Adapted from East 2008)

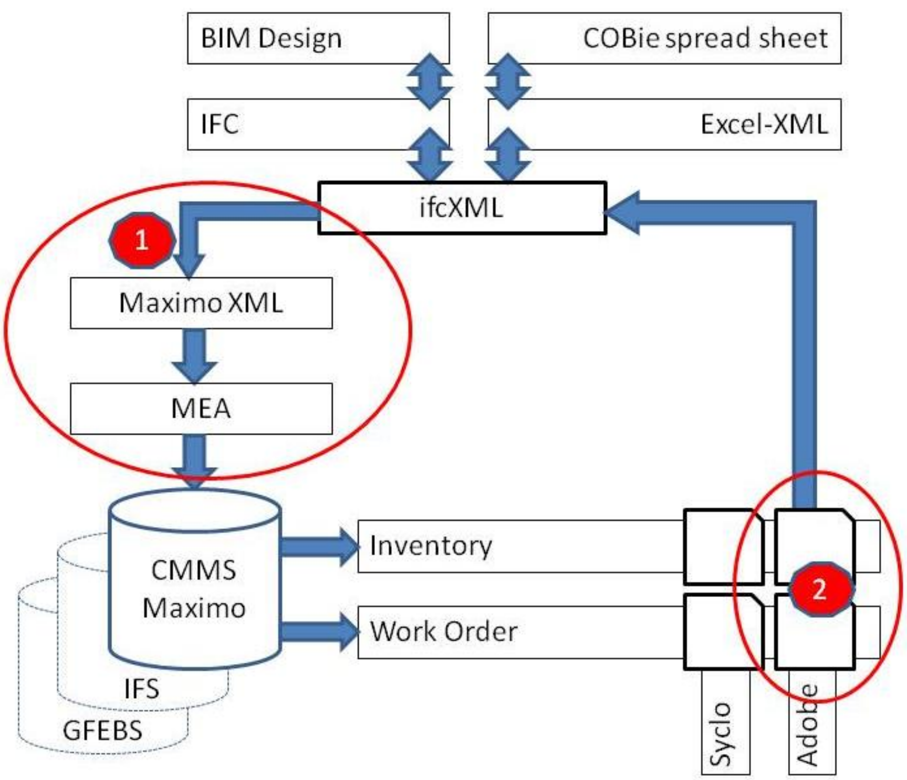

Figure 2-5. COBie Maximo project map (Source: adapted from Nisbet 2008)

CHAPTER 3
METHODOLOGY

Overview

This chapter presents the methodology of this research. A research workflow is shown in Figure 3-1. The steps taken to implement this research were as follows:

1. Conduct literature review and study existing BIM tools and functionalities in order to find out the possible needs, gaps and problems between the design, construction and FM ends.

2. Prepare and conduct a survey of industry practitioners in order to find out the real problems in the AECO industry and the practitioners' perspectives on the knowledge gap between design, construction and FM ends. In addition, conduct interviews with facility manager in order to get the facility management data requirements.

3. Acquire and study the historical maintenance work order history to investigate design defects for maintainability problems, explore the building codes and maintenance manual for the information requirements for facility maintenance activities that should be delivered from design and construction to FM.

4. Based on the survey results, work order history study, and the building code and manual investigation, establish the information and maintainability requirements for FM from the design and construction phase

5. Build a template for transferring data between design software and FM software with automatic updating on the database level.

6. Investigate existing code checking software such as SMC for maintainability checking in the design phase, and develop Revit Add-In tools for maintainability checking in the design software

7. Validate the tools and templates developed in previous phases with case studies.

BIM-Assisted Facility Management Survey

This survey was designed to assess the status of Building Information Modeling (BIM) implementation in the operation and maintenance phase of a building's life cycle. This survey was designed to discover the perceptions of the practitioners from AECO industry about the necessity of maintainability considerations in the design and construction phases, to evaluate how BIM is being used in post-construction phase and whether Operations and Maintenance factors are considered early on in the design and construction process. In addition, the survey also allowed for the collection of design defects that are revealed in the O&M phase. The respondents were also queried about maintenance problems in order to discover real design defects problems for maintainability issues. The survey should be continued as a long term effort to collect design defect information and store it in a database for the use in the improvement of future designs.

Open-ended Questions

In order to get descriptive knowledge from the respondents, many questions in this survey are open-ended questions. For the open ended questions, the analysis steps were as follows:

- Scan through the answers and look for common themes
- List major themes of responses
- Set a variable for this question
- Set a value for each theme group.
- Go through all the responses and set the answer for each respondent to the corresponding value

For multiple responses questions, each of the answers were set as a variable in SPSS, the value for each variable was 1 or 0 indicating whether the respondent choose it or not. During analysis, multiple response sets for all the variables under each question were defined. Frequencies were calculated from the multiple response sets automatically in SPSS.

As shown in Appendix A, the Friedman test was used for question 14 of the survey to test the perception difference under different conditions for the same group of people.

Friedman Test

The Friedman test is a non-parametric alternative (distribution-free) to the one-way repeated measures analysis of variance. It is used when you take the same sample of participants or cases and you measure them at three or more points in time or under three different conditions (Pallant 2011). The Friedman approach tests the null hypothesis that k related variables come from the same population. For each case, the k variables are ranked from 1 to k. The test statistic is based on these ranks (IBM 2011).

The computational formula of the Friedman's Rank test is chi-squared distributed, the test statistic is Friedman's Chi-Squared and is computed as

$$\chi_f^2 = \frac{12}{Nk(k+1)}\sum \mathrm{R}_\mathrm{i}^2 - 3\mathrm{N}(\mathrm{K}+1)$$

where N is the total sample size, k is the number of within-subjects conditions, and $R_i$is the sum of the ranks for condition i (Berkman and Reise 2012).

Case Study

A case study of an exhaust fan from Foster's (2011a) article is used to demonstrate how to solve the maintainability problems in the design phase. This case study is aimed to validate the Revit Add-In tool Accessibility Checker developed in this study. The Revit MEP 2012 BIM authoring software is used to model the scenario. Solibri Model Checker (SMC) is used as a partial solution of this problem. A Revit Add-In command named "Accessibility Checker" has been developed and implemented to check the accessibility of the exhaust fan. An invisible solid box is built when running the accessibility checker. All the items that are in the solid box is highlighted as obstacles inhibiting access to the selected equipment. Microsoft Visual Studio 2010 is used to develop the command. The Revit API software development kit sample Add-Ins and geometry and component relationships examples were used in developing the Accessibility Checker (Autodesk 2010; Ye 2011).

Construction organizations have problems in BIM adoption because there is no clear guidance or best practice study for them to learn from and build up their capacity to achieve their competitive advantage (Arayici et al. 2011). This study investigates different BIM execution plans in order to build up the policies that can help the construction industry figure out their own BIM implementation plan from others' best practice. BIM implementation plans cover more items than are included in the scope of this research. The part of BIM implementation plan explored here is BIM-assisted O&M.

Tools Used for Maintainability Checking

Database Connection

As shown in Figure 3-2, the first step of this research is to identify the needs and possible solutions for the requirements of facility management. Existing FM software is examined and interviews were conducted with several facility management staff. Although current facility management software may still have some problems such as not including enough information fields for maintenance work, it is not the focus of this paper. The information required by the software and other necessary information are added to the BIM model as parameters. Information needed for the software includes: Location ID, Building, Room Number, Floor, Description, Sq Feet, Requestor, and Phone. Description, requestor and phone should be inputted by the end user and is not related to the BIM models. So those three fields are not considered for parameters. Instead, manufacturer's name, manufacturer's contact information, location of equipment, equipment model number, and warranty expiration date are added to the BIM model as shared parameters.

The BIM tool chosen here is Revit MEP 2012 as we focus our problem on MEP system maintenance. The functionality of Revit MEP to hold the shared parameters, which can be used for multiple projects and exported to an external database, is investigated. The Revit template is built using the parameters created for maintenance purposes. DBLink connections that can export Revit data to external databases such as Access are investigated.

A case study using an education building is conducted to validate the proposed method for automatically updating information between BIM software and FM software.

Microsoft Visual Studio

Microsoft Visual Studio 2010 is used to develop the command “Accessibility Checker” using C # language. The Revit API software development kit sample Add-Ins and geometry and component relationships example was used in developing the Add-In (Autodesk 2012, Ye 2011).

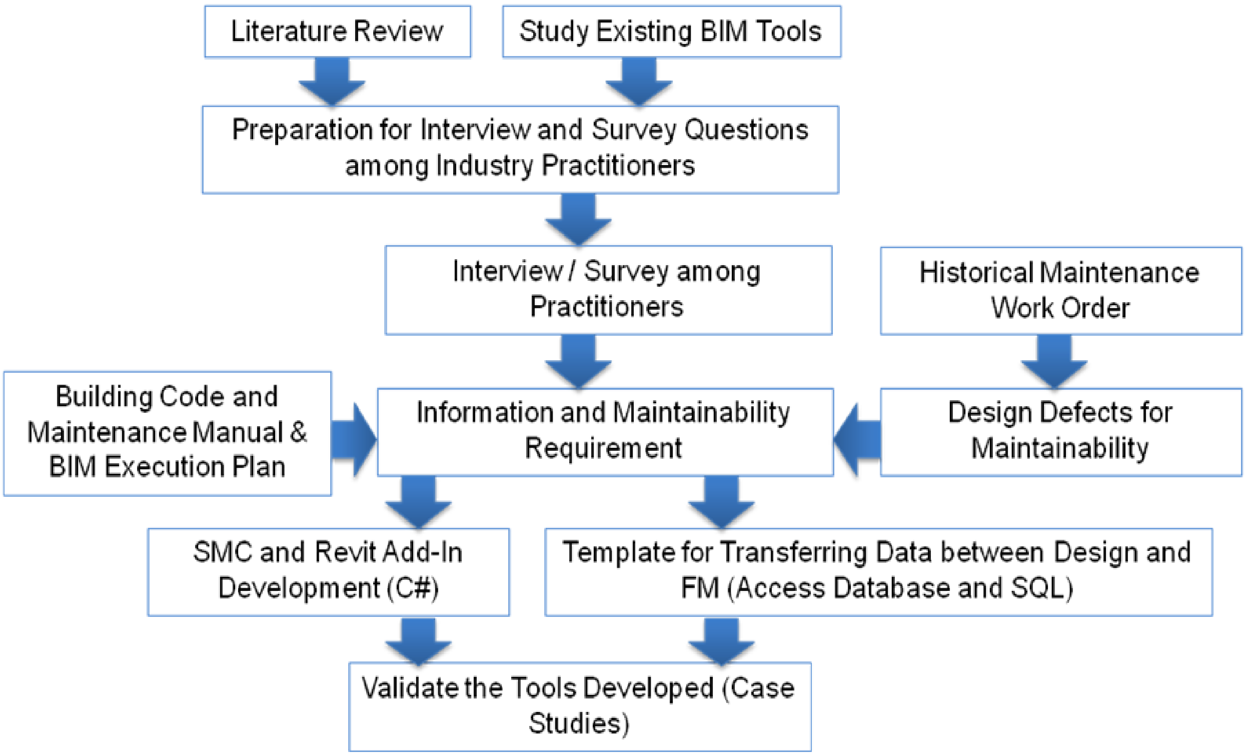

Figure 3-1. Research workflow

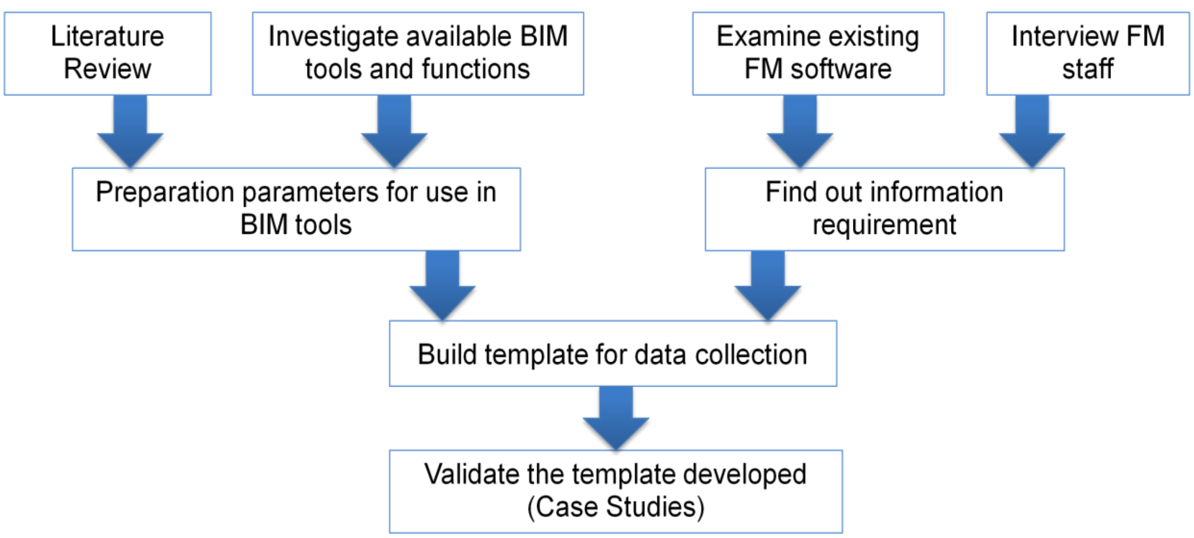

Figure 3-2. Process for database connection between BIM and FM

CHAPTER 4
THE SURVEY RESULTS

The survey was distributed in a variety of methods: (1.) through Stevens Construction Institute's news letter, (2.) through LinkedIn groups related to FM including: Facility Managers Building Owners Network, Building Owners and Managers Association International (BOMA), and Integrated Facility Management (IFM), and (3.) through an email list, collected by the author, combined with COAA Owners from Higher education, K-12, government and some organizations. It was also distributed to the Florida State University System (SUS) facility management department. Through March 7, 2012, only 12 complete responses had been received. With the help of the buildingSmart Alliance, the survey was distributed again on March 24, 2012, and through April 13, 2012, there were 693 visits, 22 partial responses and 38 complete responses. Since it is not possible to determine the exact number of people who received the survey link because people who got it had the ability to forward it to anyone they thought suitable, the response rate can only be calculated based on the number of visits and the number of complete and partial responses. The response rate was (38+22)/693=8.66%, while the effective response rate was 38/693=5.48%.

Part I: Demographic Distribution

The respondents of this survey come from the following organizations as shown in Figure 4-1. Architects constituted the largest proportion (8, 21.1%), followed by construction managers and facility managers (5, 13.2%), consultant companies (4, 10.53%), higher education managers (3, 7.9%), owners (3, 7.9%), general contractors (2, 5.3%), design builders (2, 5.3%), two software developers and four other organizations including one laboratory, one specialty subcontractor, one attorney and one research institute.

Different roles in the same company may have different perspectives and ideas. Figure 4-2 shows the distribution of the respondents' role in their companies. Upper managers constituted 14 out of the 38 (36.8%) respondents, followed by eight project managers and project engineers (21.1%), five facility managers (13.2%) and five architects (13.2%). Management level respondents constituted two-thirds of all the responses. Even when the survey was specifically distributed to maintenance related staff or MEP engineers, however none of them answered the survey. The reasons behind this may be: first, maintenance staff themselves are not familiar with BIM, so after they read the instructions accompanying the survey, they were not able to respond. Secondly, they may not have convenient access to the computer or web as management level respondents do.

The respondents' organizations were involved in almost all segments of the construction market including public (6, 15.8%), health care (5, 13.2%), education (7, 18.4%), private (1, 2.6%), commercial (11, 28.9%)) and residential (1, 2.6%), and there were five (13.2%) respondents whose companies had completed projects across different market segments, but there were no respondents whose company had taken on any projects in the infrastructure area. The detailed distribution of market segments is shown in Figure 4-3.

As shown in Figure 4-4, the respondents' BIM experience ranged from "no experience" to "expert." Among the 38 respondents, only nine (23.7 %) considered themselves as experts, and five (13.2 %) defined themselves as advanced BIM users.

Ten (26.3 %) of them described themselves as intermediate users. Nine (23.7 %) respondents classified their BIM experience level as beginners and five (13.2 %) of the respondents had no experience with BIM projects.

In order to determine the objective BIM project involvement from the responses, the proportion of BIM projects among new projects in the past 12 months was calculated from the respondents' answers about their number of new projects and the projects that used BIM. As shown in Figure 4-5, among the 34 effective responses, seven respondents (20.6 %) had no BIM project for the last year. Seven of them (20.6 %) had less than 10% of their projects that utilized BIM. There were 12 (35.3 %) respondents who utilized BIM in all their new projects. From Figure 4-5, the BIM utilization of these companies is polarized. The company either uses BIM for all their projects or uses BIM for a very limited proportion of their new projects.

Part II: Perceptions of BIM-Assisted Operations and Maintenance

This survey was aimed at collecting the perceptions from people working in the AECO industry. Some responses from software developers and attorneys have been excluded, because their understanding of facility maintenance might not be consistent with AECO practices. As a result, for part II, there were 32 effective responses.

As shown in Figure 4-6, there were 32 effective responses as to whether maintainability was taken into consideration during the design and construction phases. Twenty-eight (87.5 %) of the respondents indicated that they have considered maintainability somewhat in the design and/or construction phases, while 20(62.5 %) of them have considered it in both the construction and design phases. Only four (12.5%) respondents had never experienced taking maintainability into consideration in the design and construction phases. From the responses, it seems that maintainability has already been thought of by most of the practitioners.

From Table 4-1, the Pearson Correlation between organization types and maintainability is not significant at the 0.05 level (0.197>0.05). There is no relationship between Organization type and maintainability, which means that the answers from the respondents from different organizations about maintainability consideration were not significantly different.

As shown in Figure 4-7, there were only three (9.4%) respondents who indicated no involvement of FM personnel in both design and construction phases, eight (25.0%) responses indicated FM involvement in the design phase, five (15.6%) respondents experience FM involvement in construction phase, and 16 (50.0%) out of 32 responses had FM personnel involved in both the design and construction phases.

As shown in Figure 4-8, among 32 responses, 11 (34.4%) of the respondents noted that FM staff gave design and construction teams some general guidelines of equipment maintenance, 12 (37.5%) gave specific requirements, which is the best practice, compared to other groups, four (12.5%) of the respondents thought this was not applicable and five (15.6%) of the respondents indicated that their FM requirements varied case by case. For example, the FM staff would be involved in reviewing the drawings before construction in order to avoid maintainability issues or FM staff would check the cost and carbon impact of activities. One (3.1%) respondent used the BIM model to store information, but what information was needed depended on what FM staff asked for each time. One (3.1%) respondent indicated that FM staff would inform the design and construction teams about the lessons they have learned in the past in order to prevent future problems. Other responses included:

- Provide feedback based on lessons learned
- Review drawings and mark them up before construction docs for all issues
- Submit info they want to be included in the Federated BIM
- Cannot answer for the owner for items 8-10. Filled in only as a place holder.
- Cost and carbon impact of activities.

As shown in Figure 4-9, five (15.6%) of the respondents indicated that the manufacturers have provided adequate information for equipment maintenance activities, while 23 (71.9%) thought that they got some information from manufacturers, which indicated there was not enough information for equipment maintenance activities. Three (9.4%) answers showed no information from manufactures. One (3.1%) BIM consultant responded that they acted on a case by case basis, and that they could get the information from the corresponding parties if FM staff or owners asked for it.

For the information delivery method, respondents can choose any delivery method they have ever used (multiple choices). As a result, the total number of responses is more than the number of respondents because some people choose more than one delivery format. As shown in Table 4-2, almost half (48.4%) of the projects still delivered documentation in a physical paper copy format, 71.0% of the projects were delivered in a digital format(CD or DVD), 25.8% of the respondents experienced BIM delivery with specification information and 22.6% respondents indicated a BIM delivery that could be integrated into CMMS.

In order to determine the most-frequently occurring maintenance issues that the respondents had experienced, they were asked to list the top three maintenance problems they had experienced as open-ended questions. Some of the respondents reported more than three maintenance issues and some of them did not respond. From the 32 responses, there were 22(68.8%) of who answered this question as shown in Table 4-3. The answers were divided up into ten categories, which were then analyzed. If the respondent mentioned the corresponding category, the variable value was set to 1; otherwise the value was set to 0.The response frequencies are shown in Table 4-4.

Other maintenance problems that the respondents reported include vandalism and misuse of equipment, commissioning, auditing, and lack of standards and guidelines for owners to follow. These problems are related but were not the focus of this study, so they were all classified as others.

Each respondent was asked to list three problems (some respondents listed less than three and some listed more than three). The total number of responses was more than the number of people who answered the question, so the total percent of cases is more than 100%. As shown in Table 4-4, information accessibility (reported 11 times by the 22 respondents to this question) was the top maintenance problem that the respondents reported, which means 50% of the respondents had experienced this problem. 31.8% of the respondents had experienced accessibility/clearance issues, and 22.7% of the respondents complained about the poor as-built documents. Information accuracy, budget and cost, lack of trained personnel and lack of preventative maintenance were also reported as problems that they had experienced.

Significance of maintainability problems. The null Hypothesis tested was:

H_0: There is no significant difference across the five different maintainability problems.

Table 4-5 shows the respondents' experience with the maintainability problem frequency. The respondents were asked to choose the frequency of each maintainability problem listed (the respondents had the freedom to leave one or more problem blank, so the total number of responses for each problem were not the same). A non-parametric method, the Friedman test, was used for determining the difference across different occasions for the same group of people. The descriptive statistics of the five variables are shown in Table 4-6. The 23 respondents rated all of the five problems listed in the questionnaire, the mean values of the frequency is 31.5% for lack of equipment accessibility, 33.7% for poor design of equipment layout, 41.3% for lack of adequate space in mechanical room, 53.3% for lack of space in the ceilings to contain MEP systems and 35.9% for limited space of AHU filter access.

As shown in Table 4-8, the significance level is 0.005 which is less than 0.05. The results of this Friedman Test indicate that there are statistically significant differences in frequency across the five different maintainability problems. The significant difference is somewhere among the five variables. From Table 4-7, the lack of space designed in the ceiling to contain MEP systems is the most frequently occurring problem, followed by lack of adequate space for the mechanical room, limited space for AHU filter access, poor design of equipment layout, and lack of equipment accessibility.

As shown in Figure 4-10, there were 28 effective responses for the question about maintainability assessment in the design phase. Fifteen (53.6 %) of the respondents indicated that they assessed maintainability in the design phase, seven (25.0%) of them indicated no assessment in the design phase, and five (17.9%) respondents pointed out that the assessment of maintainability depended on the owners' requirement.

As shown in Figure 4-11, there were 28 effective responses for the question about maintainability assessment in the construction phase. Seventeen (60.7%) of the respondents indicated that they assessed maintainability in the design phase, four (14.3%) indicated no assessment in the construction phase, and four (14.3%) respondents noted that the assessment of maintainability depended on the owners' requirements. Two (7.1%) respondents indicated that they tried to assess maintainability in construction phase, but it usually failed as it was late. In addition, one (3.6%) architect specified that there was always an attempt to assess maintainability but often, when they bid the job, there were substitutions that changed equipment with unintended consequences. This respondent indicated that they tried to assess maintainability in the construction phase too, but often when they bid the job there were substitutions that changed equipment with unintended consequences. Another respondent, who is a construction manager, pointed out that they found some problems during the construction phase but did not often make changes because of change order costs.

As shown in Figure 4-12, there were 26 effective responses for the question about maintainability assessment in the operation phase. Nine (34.6%) respondents indicated that they assessed maintainability in the operation phase, nine (34.6%) indicated no assessment in operation phase, three (11.5%) respondents pointed out that the assessment of maintainability depended on the owners' requirement and three (11.5%) respondents pointed out that they did maintainability assessment in the operation phase but it was always too late to correct problems.

Sixteen respondents answered the question about the resolution of a design flaw that led to a maintenance problem in the operation maintenance phase. Most of the answers specified “re-design”, “change order” and “re-location” to correct the existing problem. Some of the answers indicated that legal action always accompanied the re-design work.

Fifteen respondents answered the question inquiring about the facility maintenance management system software that they were using. The responses indicated that there are many FMMS software packages on the market, which may be a problem for integration of BIM and FMMS since different software platforms have different attributes and standards (Table 4-9).

There were 24 responses to the question about the work order systems that the respondents were using. Fourteen (58.3%) of the respondents believed that they had enough information to complete the work and, 10 (43.5%) of them thought that the current work order system could not provide enough information to carry out the work requested.

As shown in Figure 4-13, there were 24 effective responses to the question about whether the respondents used BIM models for the facility operation and maintenance phase if their projects used BIM models in the previous phases. Six (25.0%) respondents used BIM models for facility operation and maintenance, 17 of 24 (70.8%) did not use BIM models in the FM phase even though they used the BIM model in previous phases. Among these 17, three (12.5%) were planning plan to begin using the BIM model for the FM phase. One (4.2%) respondent pointed out that they tried to tie the BIM model to FM but the number of polygons made the model too big and cumbersome so the staff printed copies and placed them in binders. From Figure 4-14, even some BIM experts and advanced users did not use the BIM model for the FM phase.

In addition, as shown in Figure 4-15, even when a BIM model was in use, only two (9.1%) of the 22 respondents thought that the model had enough information for facility operation and maintenance, eight (36.4%) respondents believed that the BIM model had part of the information needed for O&M and that to gather enough information, manual input was still required. Five (22.7%) respondents thought that the BIM model had no information useful for O&M. All the other respondents who had answered this open-ended question indicated that since they had not used the BIM model for FM, they had no idea about the information that it could provide for O&M.

As shown in Figure 4-16, the respondents enumerated the information needed for an equipment work order. The respondents for this question were asked to select all the answers that applied, so the total percent of cases is more than 100%.The required information listed was the name of the manufacturer, location of the equipment, O&M repair instructions, contact information for the manufacturer, equipment model number, cut sheet, and down time. Some responses listed under "Others" were repair history, date of installation, warranty information, geospatial link, connectivity and affected spaces as required information for equipment work orders.

When asked whether the respondents had experienced any uncompleted work orders (see Table 4-10), there were six respondents who had such experience, four respondents answered no, and all the others were not sure or had no idea. For the six "yes" responses, the reasons for these uncompleted work orders were as follows:

- Work order information incomplete
- Lack of material to complete the work order or lack of information
- Employees not following direction
- Waiting for parts, funding or management decisions
- Lack of information or parts (Most Frequently mentioned)
- Lack of staff expertise or lack of budget.

Based on the respondents' answers the information for facility operation and maintenance that is typically hard to locate includes:

- Equipment operating parameters and spare parts
- MEP information, specifications and warranty
- Electrical panel information
- Make, model, and O&M manuals
- Security and HVAC details
- Work order history information
- Up-to-date as-built plans

This information is easy to input into the BIM model and made available to FM personnel. The method of collecting and delivering such information is discussed in Chapter 5.

In response to the last question of the survey, all 32 respondents believed that it was necessary to take maintainability into consideration in both the design and construction phases. This consensus was that no matter what roles the respondents held, they all believed that it was beneficial to take maintainability into consideration in the early phases of a project.

Discussion of Survey Results

The survey did not collect information from all the parties it was intended to, such as structural engineers, structural fabricators, MEP manufacturers and suppliers. The survey results indicated that the industry practitioners believed that maintainability issues should be considered in the design and construction phases and they put forward the efforts to make it happen. As shown in Figure 4-6, 28 of the 32 respondents had considered maintainability in the design and/or construction phases. In addition, from Figure 4-7, half of the respondents indicated FM personnel involvement in both the design and construction phases. In addition, more than half of the respondents assessed maintainability in both the design and construction phases (Figures 4-10 and 4-11). However, 43.5% of the respondents still expressed that they did not have enough information for work orders in the operation phase and maintainability problems still happened fairly often. As shown in Table 4-6, the mean value of lack of space in ceiling is more than 50% of the time. For all the other problems, the mean values were about 30% of the time. These results indicate that even if FM personnel got involved in the earlier phases, the existing practices cannot prevent maintainability problems in the design and construction phases. Better practices and technologies are needed to carry information from the design and construction phases to the operation phase and to better implement the design for maintenance (D4M) rules. The framework of D4M for the information delivery method to carry information from design and construction to operation is discussed in Chapter 5.

Table 4-1. Organization type and maintainability consideration correlations

		Organization	Maintainability Consideration
Organization	Pearson Correlation	1	.234
	Sig. (2-tailed)		.197
	N	32	32
Maintainability Consideration	Pearson Correlation	.234	1
	Sig. (2-tailed)	.197	
	N	32	32

Table 4-2. Information delivery format frequencies

		Responses		Percent of Cases
		N	Percent	
Information Delivery Format[a]	A physical paper copy	15	28.8%	48.4%
	A digital copy on a CD or DVD	22	42.3%	71.0%
	BIM with specification information attached	8	15.4%	25.8%
	A BIM integrated into CMMS	7	13.5%	22.6%
Total		52	100.0%	167.7%

[a]Dichotomy group tabulated at value 1.

Table 4-3. Maintenance problems case summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Maintenance Problems[a]	22	68.8%	10	31.3%	32	100.0%

[a]Dichotomy group tabulated at value 1.

Table 4-4. Maintenance problems frequencies

		Responses		Percent of Cases
		N	Percent	
Maintenance Problemsa	Information Accessibility	11	24.4%	50.0%
	Accessibility/Clearance Issues	7	15.6%	31.8%
	Poor As-built document	5	11.1%	22.7%
	Information Accuracy	4	8.9%	18.2%
	Budget/cost	3	6.7%	13.6%
	Lack of trained personnel(including BIM and CMMS)	3	6.7%	13.6%
	Lack of preventative maintenance	3	6.7%	13.6%
	Software interoperability	1	2.2%	4.5%
	Cooperation and trust between parties	1	2.2%	4.5%
	Other problems	7	15.6%	31.8%
Total		45	100.0%	204.5%

[a]Dichotomy group tabulated at value 1.

Table 4-5. Maintainability problems based on frequency

	Never 1	25% of the time 2	50% of the time 3	75% of the time 4	100% of the time 5	N/A N/A
Lack of equipment accessibility	7 25.0%	8 28.6%	8 28.6%	2 7.1%	0 0.0%	3 10.7%
Poor design of equipment layout	3 11.1%	11 40.8%	8 29.6%	2 7.4%	0 0.0%	3 11.1%
Lack of adequate space for mechanical room	2 7.4%	10 37.1%	8 29.6%	5 18.5%	0 0.0%	2 7.4%
Lack of space designed in the ceiling to contain MEP systems	1 3.7%	7 25.9%	8 29.6%	5 18.6%	4 14.8%	2 7.4%
Limited space for AHU filter access	5 19.2%	7 26.9%	7 26.9%	4 15.4%	0 0.0%	3 11.6%

*The top number is the count of respondents selecting the option. The bottom % is percent of the total respondents selecting the option.

Table 4-6. Maintainability problems descriptive statistics*

	N	Mean	Standard Deviation	Minimum Value	Maximum Value
EqpAccs1	23	31.5%	.24094	.00	.75
PoorLayout1	23	33.7%	.20792	.00	.75
SpcLack1	23	41.3%	.23366	.00	.75
SpcCeil1	23	53.3%	.29488	.00	1.00
SpcFilter1	23	35.9%	.25922	.00	.75

*The variables listed in the first column correspond to variable of occasions in Table 4-5.

Table 4-7. Friedman test mean ranks

	Mean Rank
EqpAccs1	2.48
PoorLayout1	2.70
SpcLack1	3.24
SpcCeil1	3.76
SpcFilter1	2.83

Table 4-8. Friedman test statistics

N	23
Chi-Square	14.844
df	4
Asymp. Sig.	.005

Table 4-9. Facility maintenance management systems in use

Software Name	Archibus	Maximo	Asset Works	TMI	TMA	Track-it	SiteFM	AiM	EvolveFM	ArchiFM
Number of Respondents	6	3	2	1	1	1	1	1	1	1

Table 4-10. Uncompleted work order experience

		Frequency	Percent
Valid	1 Yes	6	18.8%
	2 No	4	12.5%
	99 N/A	9	28.1%
	Total	19	59.4%
Missing	System	13	40.6%
Total		32	100.0%

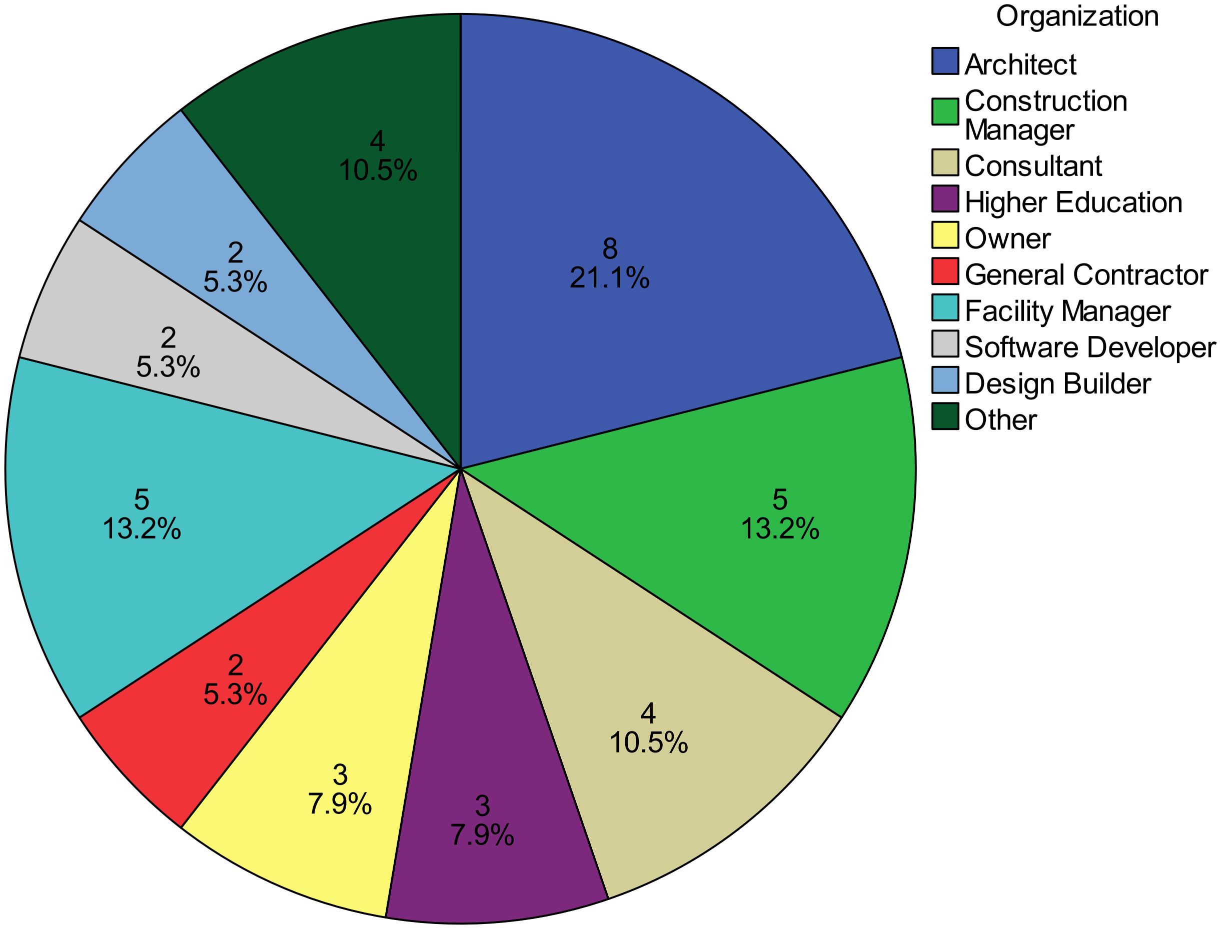

Figure 4-1. Respondents' organization

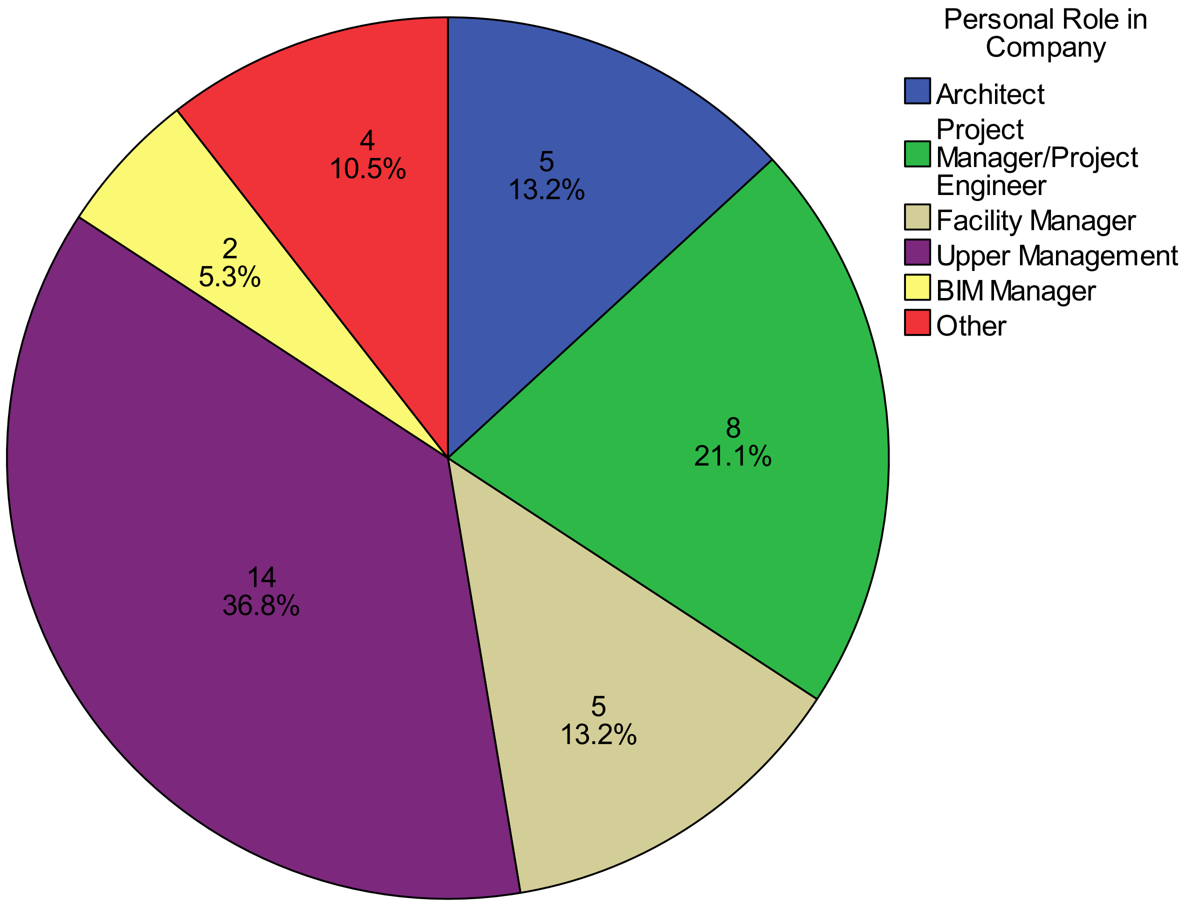

Figure 4-2. Respondents' role in the company

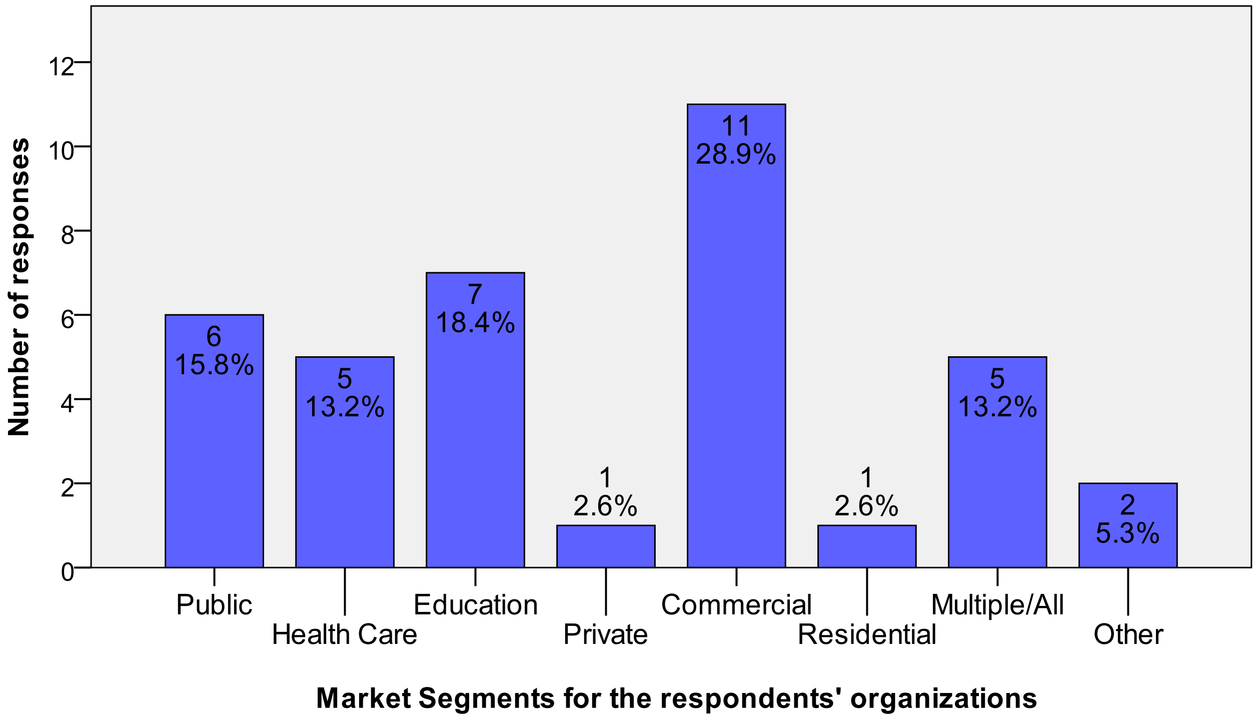

Figure 4-3. Market segments for the respondents' organizations

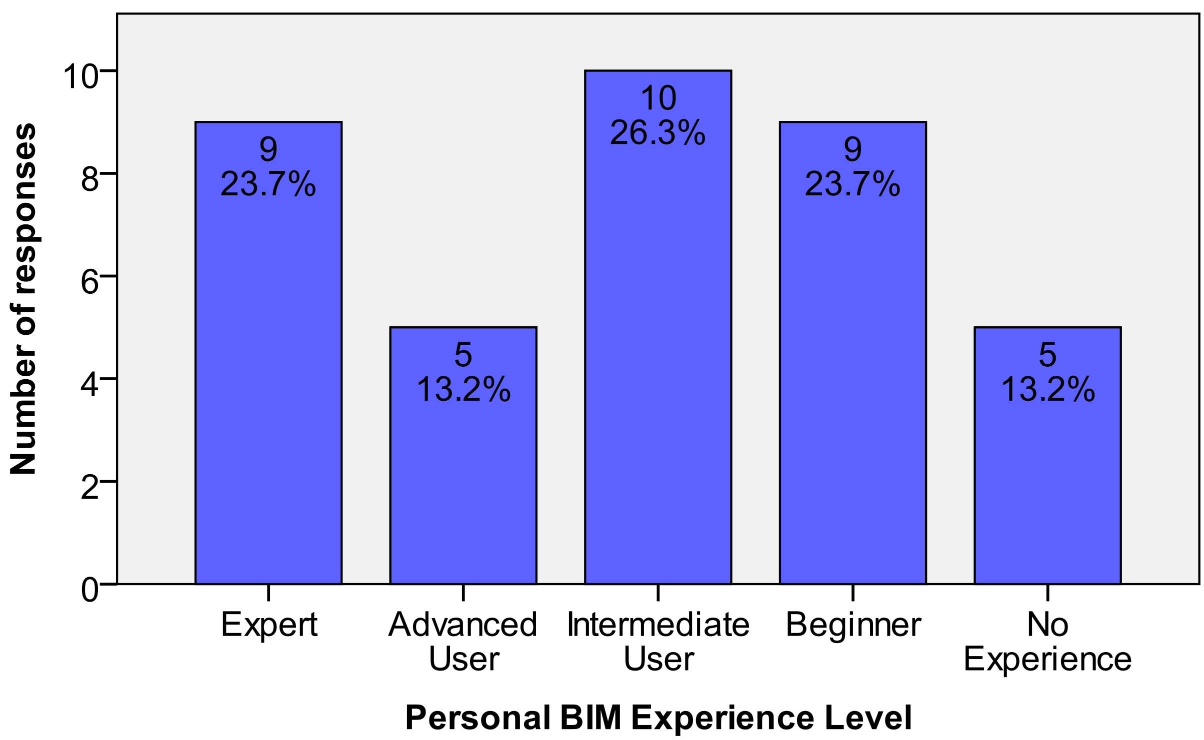

Figure 4-4. Respondents' personal BIM experience level

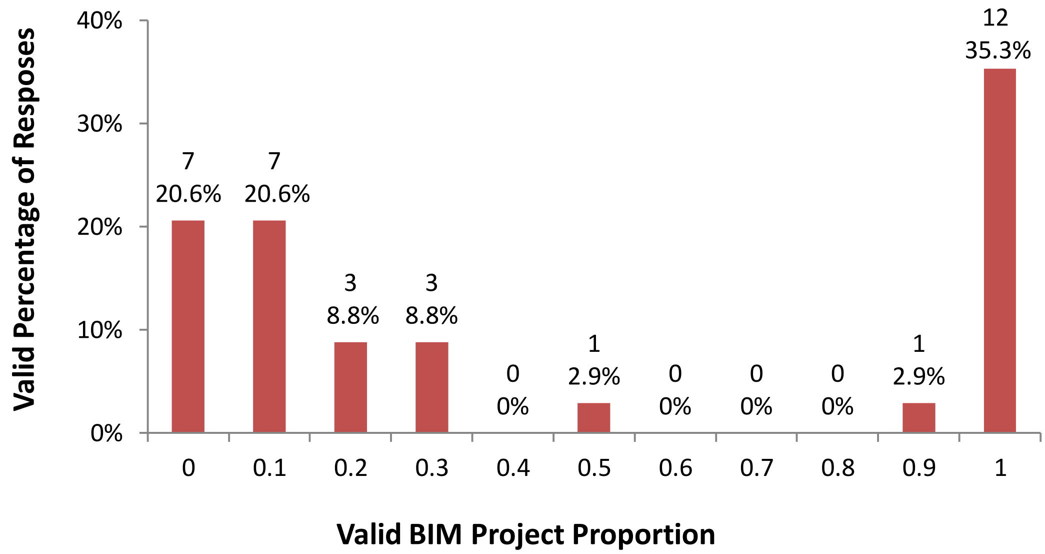

Figure 4-5. BIM project proportion

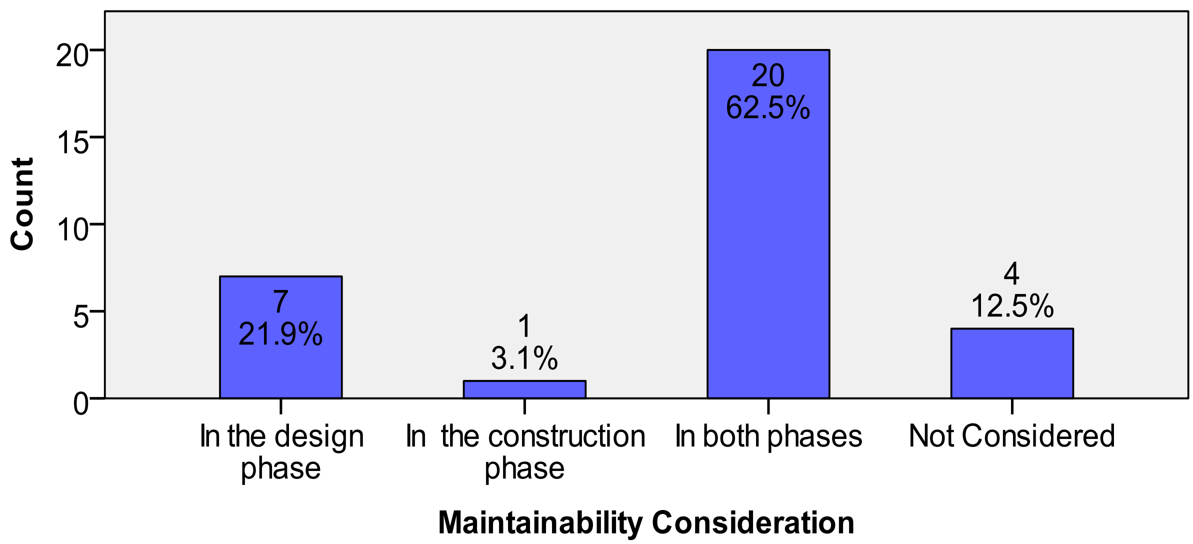

Figure 4-6. Construction phases that consider maintainability

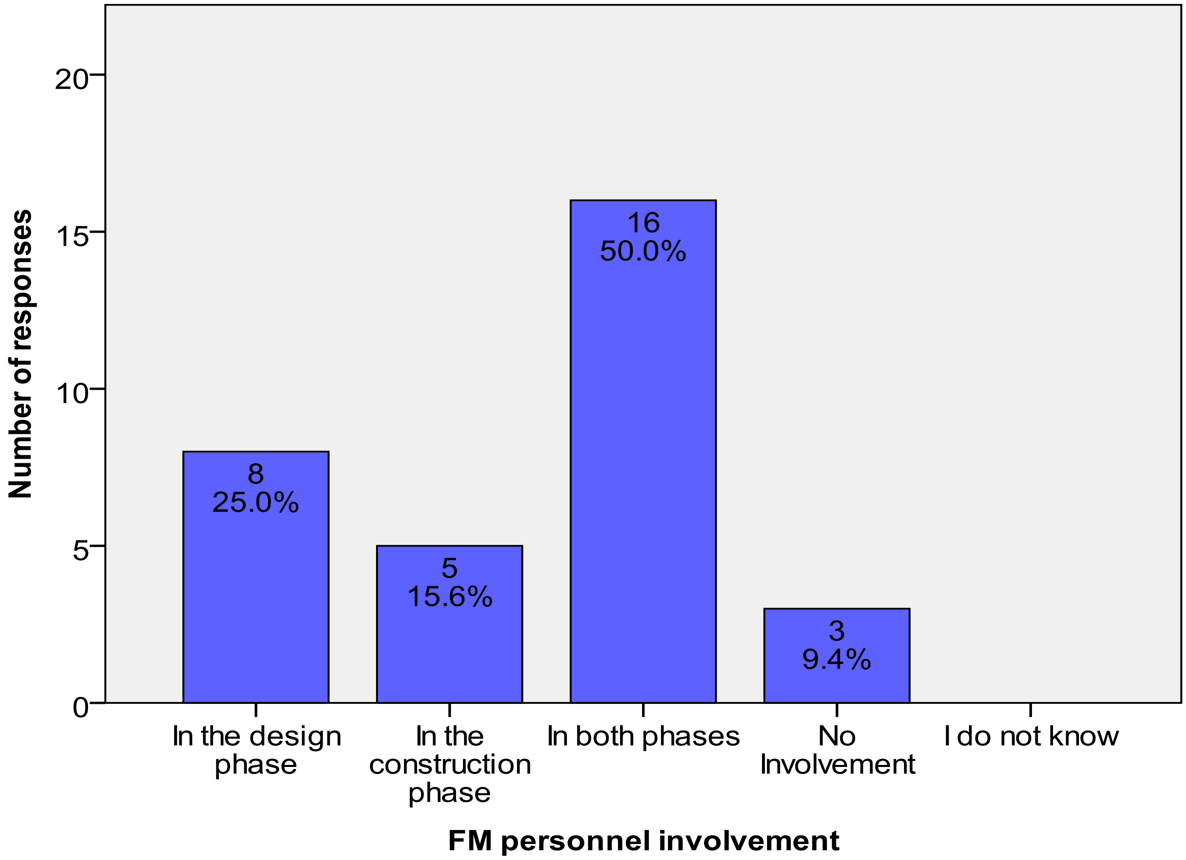

Figure 4-7. FM personnel involvement in design and construction phases

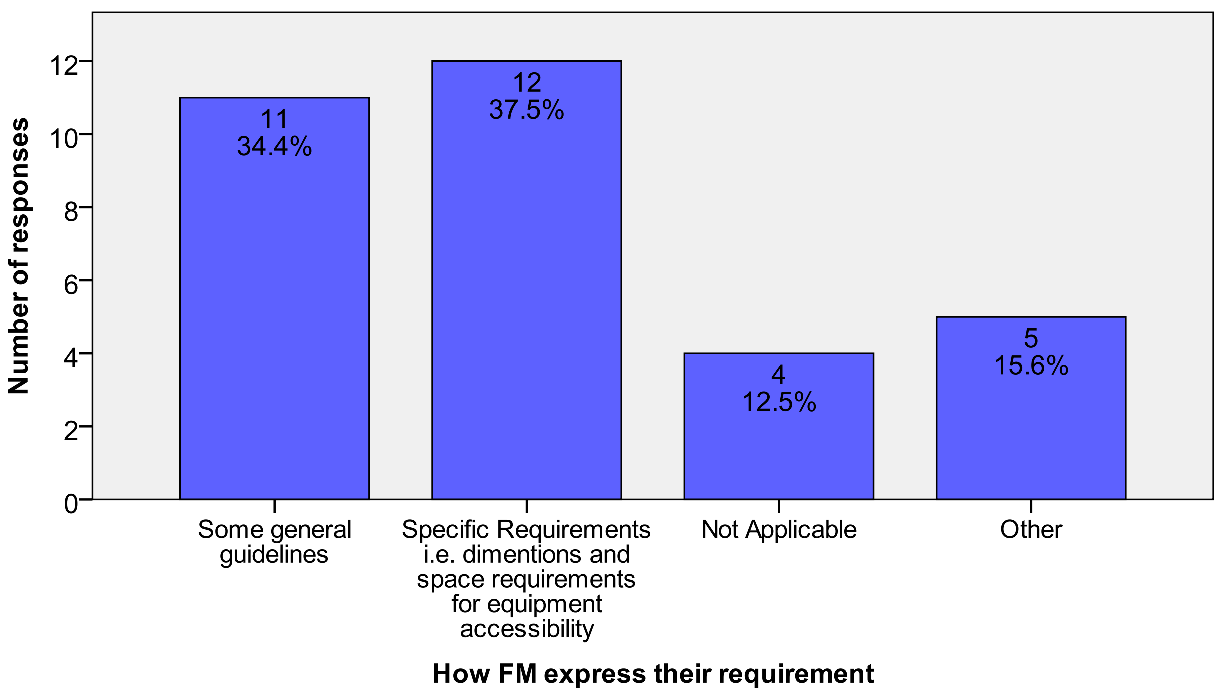

Figure 4-8. FM requirements level

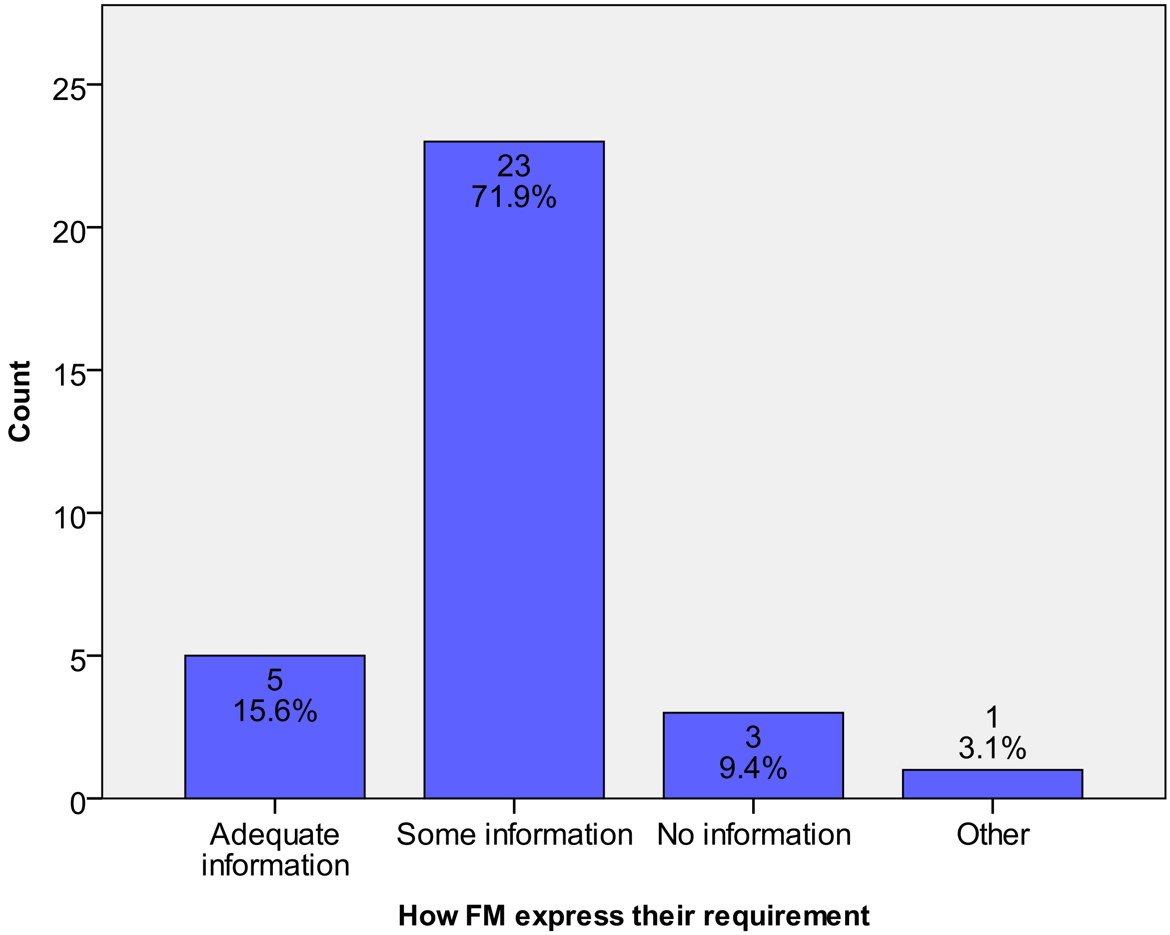

Figure 4-9. Manufacturers' information level for equipment maintenance activities

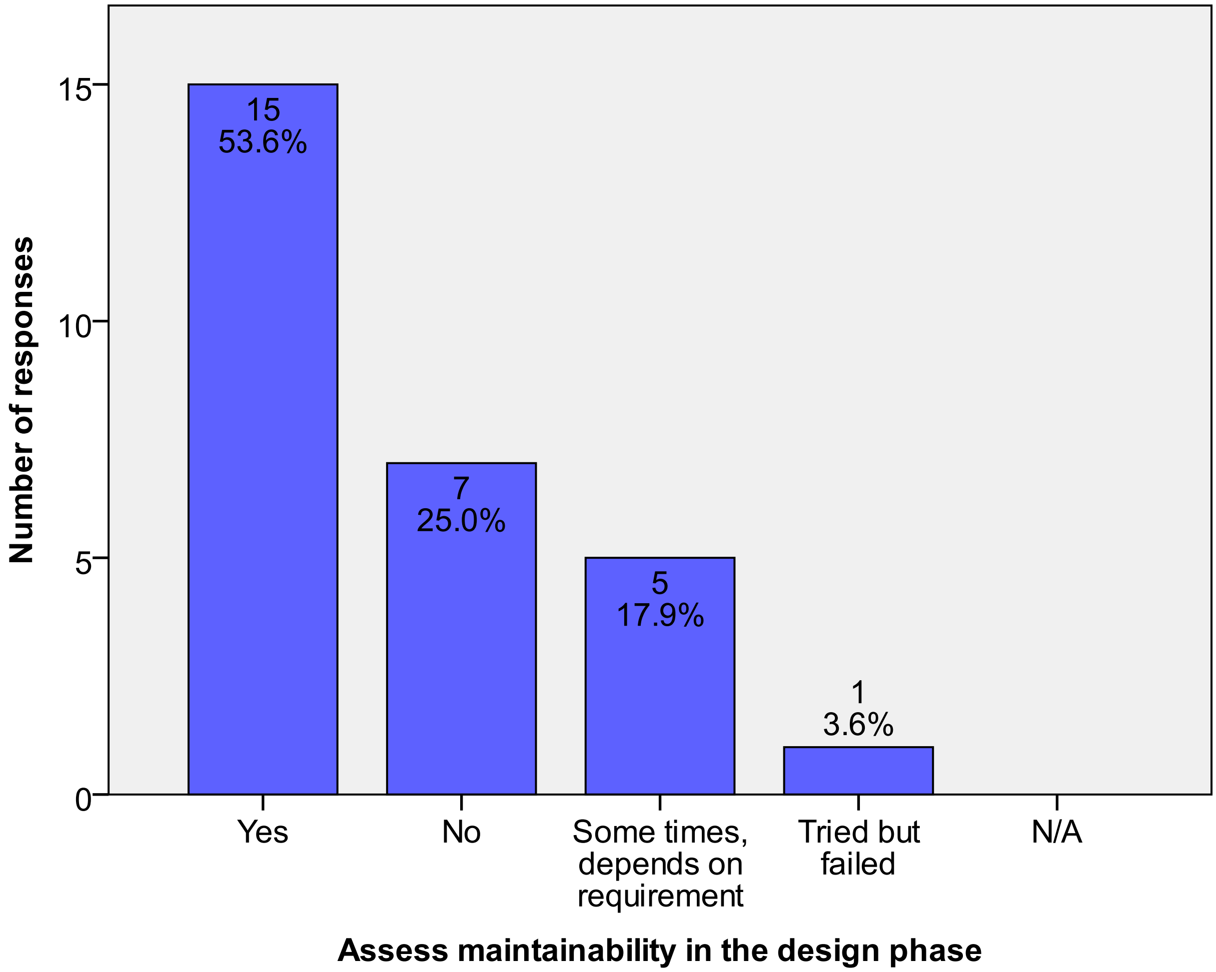

Figure 4-10. Organizations assess maintainability in the design phase

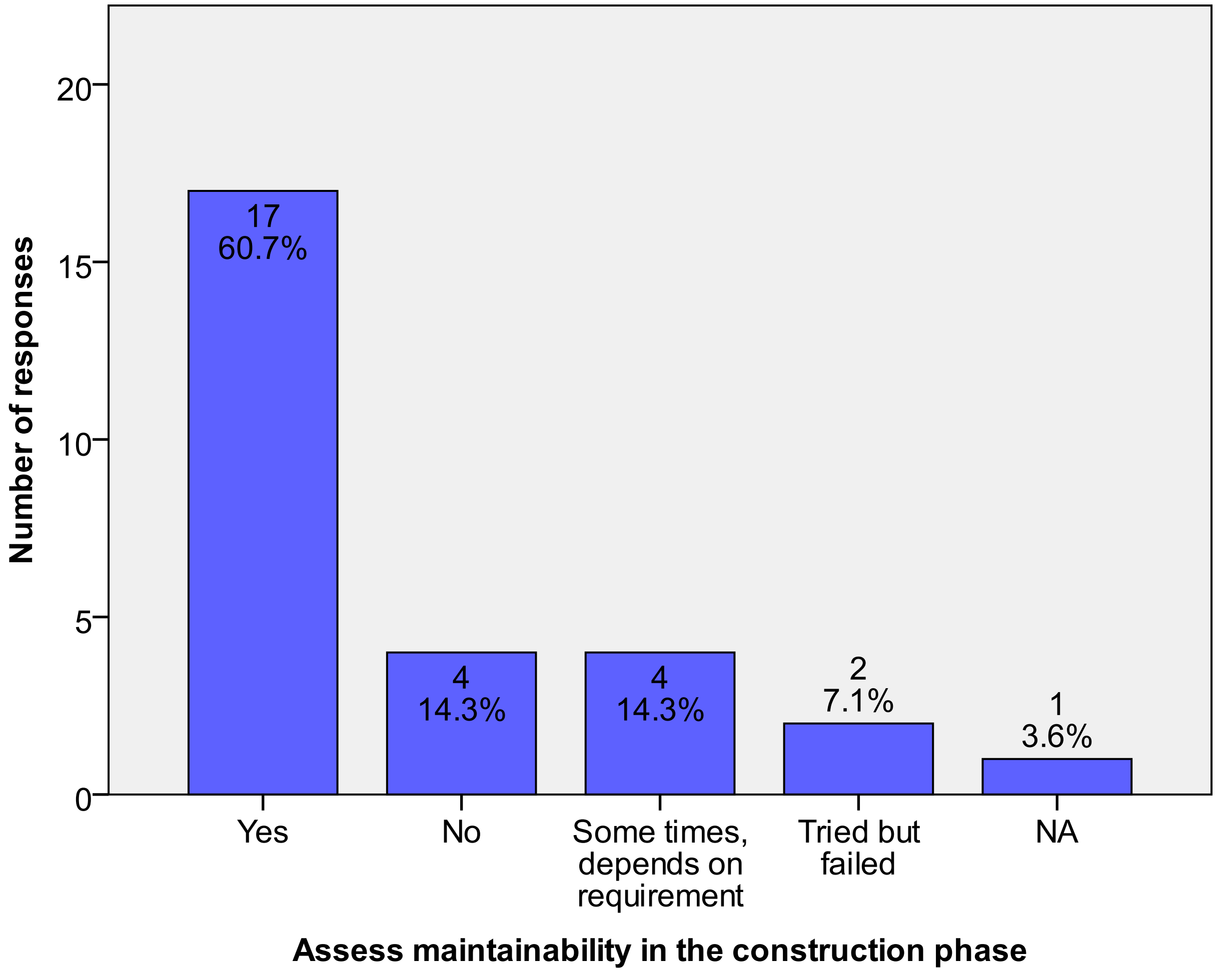

Figure 4-11. Organizations assess maintainability in the construction phase

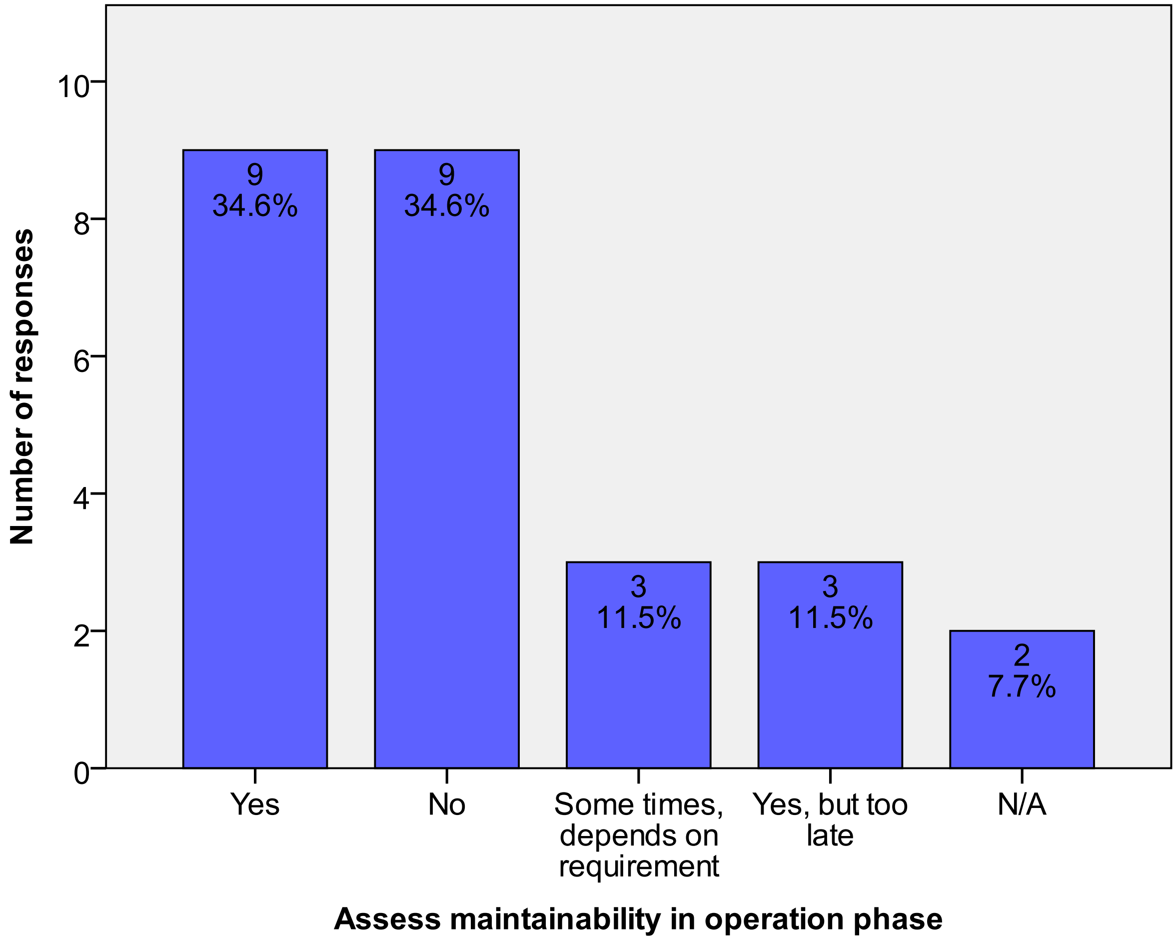

Figure 4-12. Organizations assess maintainability in operation phase

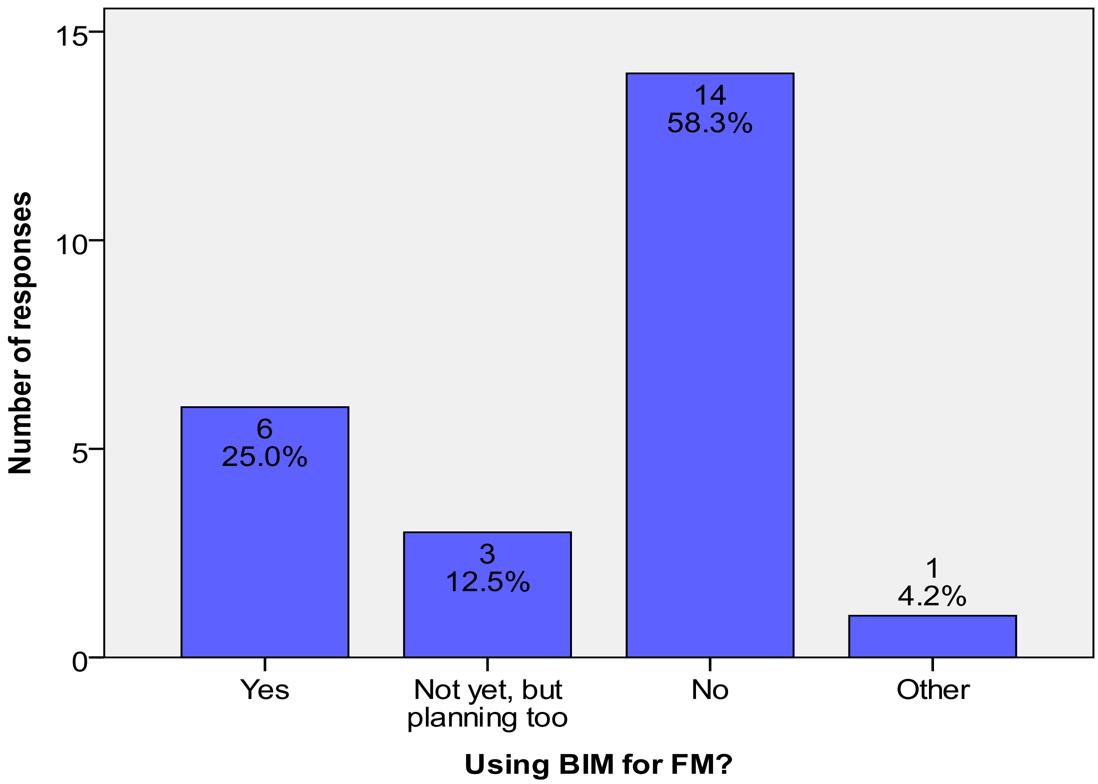

Figure 4-13. Whether using BIM for FM

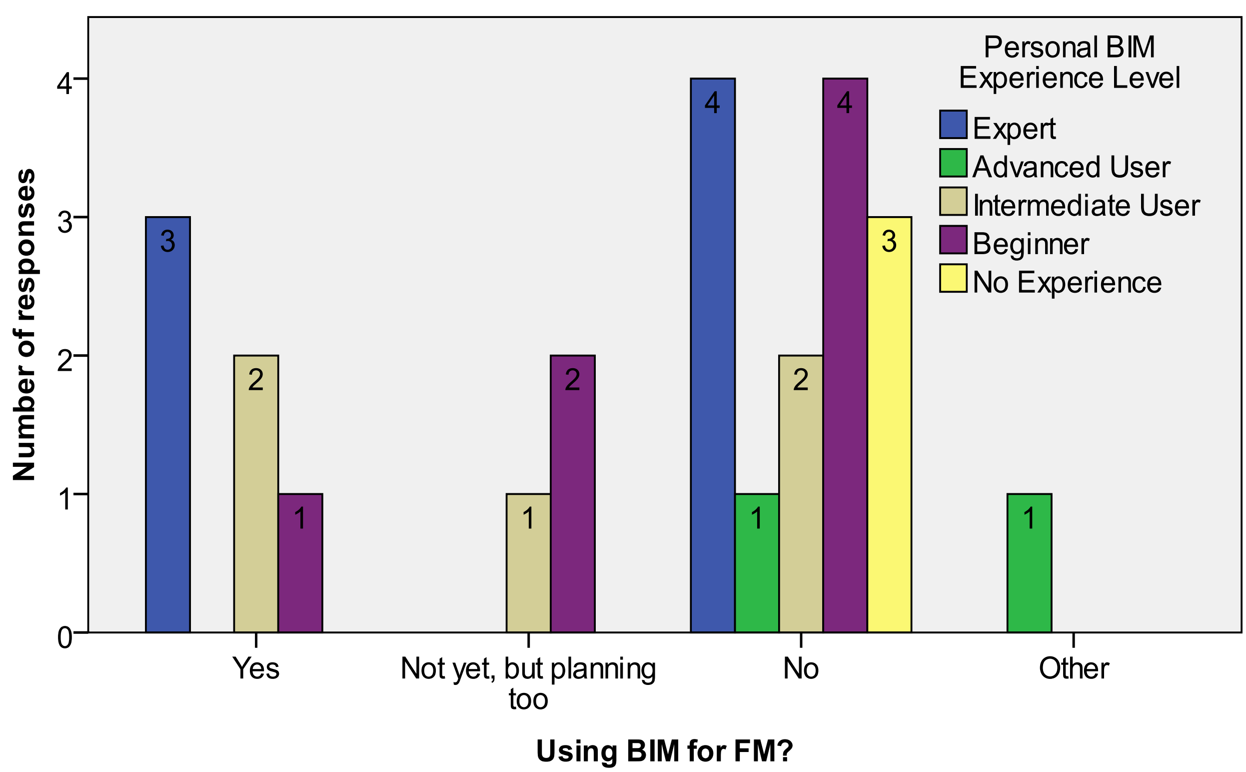

Figure 4-14. Use of BIM model for FM based on BIM experience levels

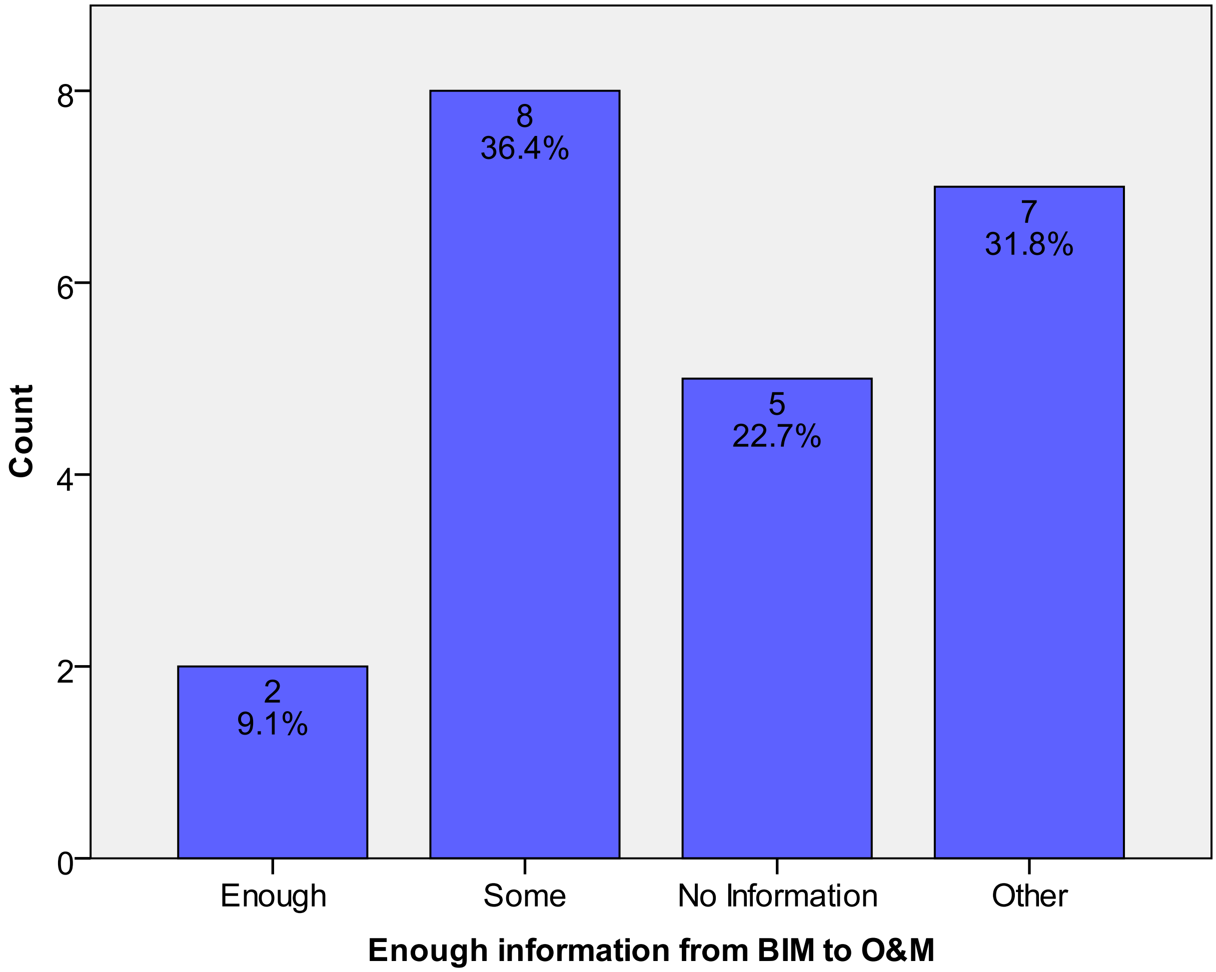

Figure 4-15. Information level from BIM to O&M

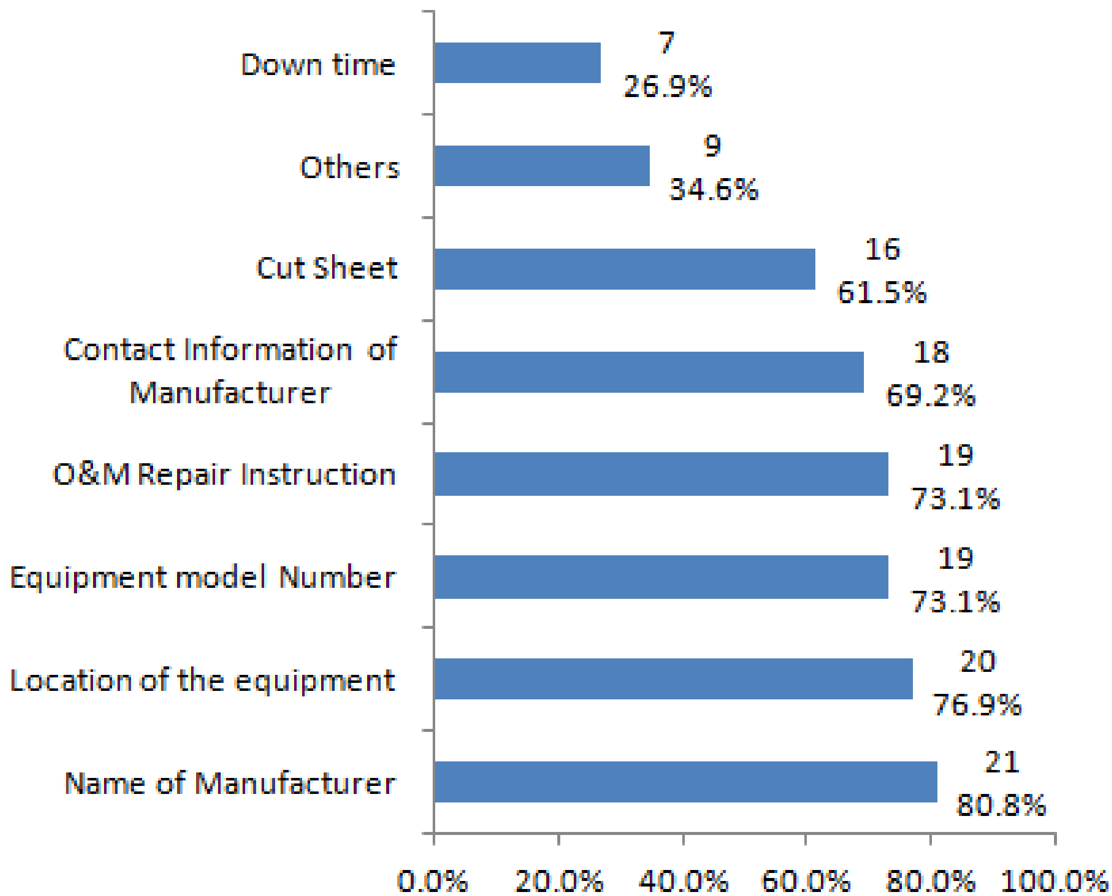

Figure 4-16. Information needed for equipment work orders

CHAPTER 5
CASE STUDY

Accessibility Checker

This case study is aimed at illustrating and validating the Revit Add-In tools developed for this research.

Exhaust Fan Example

The use of an exhaust fan (in red), as shown in Figure 5-1, had to be terminated because no solutions could be found to get access to it and fix it (Foster 2011b).

When this design was imported in clash detection software such as Navisworks™, it did not show any conflict because there was no physical intersection between the different parts. Even in the installation phase, there was no problem because the exhaust fan was installed first before other ducts and wires. But when this exhaust fan needed maintenance in the facility management phase, the maintenance personnel could not find a way to get access to this exhaust fan.

Model Checking in Solibri Model Checker (SMC)

The Revit 2012 model (shown in Figure 5-2) was exported as an IFC file and opened in SMC. As there is still an interoperability issue between these two platforms, all the conduits were lost in the IFC file. In the IFC model shown in Figure 5-3, the conduits were replaced by pipes in order to occupy the physical position of the conduits.

The rule set used to check accessibility in SMC is “Free area in front of component”. As shown in Figure 5-3, users of SMC can set the distance requirement that the specific equipment or other objects need for maintenance accessibility. SMC shows that in front of the exhaust fan, there are four items in the range of the distance requirement, so for access from the front of this exhaust fan, the designer needs to move these four items.

Revit Add-Ins: Accessibility Checker

Using the Revit Add-In tool, named Accessibility Checker, developed for this research, in the Revit 2012 environment, the user clicks on the External Tools/Accessibility Checker command as shown in Figure 5-4(a) and then chooses the location to make an accessibility box as shown in Figure 5-4(b). The box set in this command is 5 feet long. Users can always change this parameter in the background C# code: double solidBoxLength = 5.

As shown in Figure 5-4(c) and Figure 5-4(d), pipes and conduits within 2.5 feet of the selected point are highlighted in red in the Revit model. Without transfer to another software platform, the designer can decide whether this is a reasonable design or whether to move the corresponding items. Users also have the freedom to change the accessibility solid box if the accessibility requirement is different for various types of equipment. As compared to SMC, this command can find the accessibility conflict around the specific equipment.

Steps for D4M

First of all, there should be a specific BIM execution plan or BIM management plan, which carries detailed information about the maintainability requirements. These requirements should be reviewed by experienced facility management personnel before any design work begins.

Secondly, based on the BIM execution plan, rules in the Maintainability Checker Add-In tool should be set so that the designers can use them during the design phase.

Finally, after all the design work including architecture, structure, and MEP systems has been completed, the combined model should be checked based on the maintainability requirement rules in order to avoid maintainability conflicts between different systems.

Discussion of Accessibility Checker

SMC is easy to use since it requires no coding experience. Its ability, however, is restricted by the rule set it offers because there is no guarantee that all the needed requirements are already in the rule set. In addition, because of the interoperability issue between the SMC version (v6.2) used and Revit 2012, losses information were found in the IFC model during format transfer, e.g., in the exhaust fan example, all the conduit items were lost and had to be replaced with pipes. However, when a huge BIM model is exported from Revit into SMC, the lost information would be much more difficult to discover and replace.

The Revit Add-in Accessibility Checker has more flexibility to satisfy the user's requirements. However, it requires the user to have some coding experience since it has to be written in C# or VB. The software codes behind this Accessibility Checker command are specific for this case study and need to be adjusted based on the specific scenario. If all the maintenance unfriendly design issues can be solved in the design phase, the maintenance costs over the life cycle of a facility would be much lower. In addition, the specific problem in the case studied in this research, which required the existing exhaust fan to be removed and a new one installed, would not happen again.

Automatically Update CMMS with BIM Database

Since the required information and data fields have been discovered after investigating the existing FM software and interviewing FM staff, the first step to prepare the template in Revit and database export is to add the required parameters to the Revit Model. Shared Parameters are used here because they can be shared by multiple projects and families and they can be exported to ODBC and also appear in schedules. If project parameters are used, the parameters created can only be used for the current project but not shared by other projects. As the parameters are intended to be used for different projects, shared parameters are more applicable.

Revit offers the functionality to build schedules for single or multiple categories, Based on the requirements of the end user, different schedule types can be chosen. A multiple category schedule is shown in Figure 5-6 which was generated by using the shared parameters set in Figure 5-5. Based on the import format that the FM software can accept, the template created in Revit MEP can be saved as an MS Excel file as shown in Figure 5-7 or exported to ACCESS as an .mdb file through DBLink as shown in Figures 5-8 and 5-9.

Through DBLink, data behind the 3D visualization of the BIM Model can be calculated easily and as the .mdb file can be imported back to the Revit model. Any changes that happened in MS Access can automatically update the corresponding change to the BIM model after import. In addition, the users can add new fields in the MS Access database, and the new fields are shared parameters in the BIM model (Autodesk 2012). Based on what information is needed for the FM software, some data fields should be edited in the Access database before import into the FM software system because the data attributes exported from Revit 2012 may not match the requirement of the FM software used.

Maximo Case Study

Company Background

The company using Maximo, studied here, was founded in 1923. The Company and its affiliated companies have remained faithful to their commitment to produce unparalleled entertainment experiences. It is a leading diversified international family entertainment and media enterprise. This company uses Maximo as their CMMS for their maintenance departments. They also use it for the Production and Integrated Facilities Plan (IFP).

Maximo

Maximo, developed by IBM, is a computerized asset maintenance system that can provide asset management, work management, materials management, and purchasing capabilities to help companies maximize productivity and extend the life of the revenue-generating assets. Maximo can help companies create strategies for maintenance work, repair, and operations related to Enterprise Asset Management (EAM) and Information Technology Asset Management (ITAM) (IBM 2007).

The Maximo applications can be grouped into modules including assets module, contracts module, deployed asset module, inventory module, planning module, preventative maintenance module, purchasing module, resources module, safety module, self-service module, service desk module, service management module, and work orders module. The modules related to this study are the preventative and work orders modules. Under each module, there are several applications. Maximo puts applications with similar functionality into one group. For example, in the preventive maintenance module, there are two applications named master PM and preventative maintenance (IBM 2007).

Framework for BIM-Maximo Integration

Maximo has mainly four information transportation methods. First, end users can manually input information to Maximo. Second, end users can use AutoMAID technology to input information to Maximo through the Java Virtual Machine (JVM). It is more efficient to use AutoMAID than manually input by end user as AutoMAID can perform the repetitive work the end users need to do for entering the data.ButMaximo processes the data from end users and AutoMAID in the same way as screen input from the front end. Third, the BIM model may be used to develop an XML format and transfer it to Maximo XML which can transfer information into Maximo through Maximo Enterprise Adapter (MEA). This is the same approach as described in session COBie interoperability with MAXIMO of Chapter 2. Fourth, the required information can be exported from BIM model into flat text file such as .xls, .txt or .csv files, and SQL can be used to push information into MEA or SAP software (an ERP Software) which can communicate with Maximo. In this chapter, the fourth way is demonstrated.

Revit Templates for Maximo Data Requirement

One data requirement example provided by the company studied was provided in the MS Excel format. The table shows the data requirement for this company to build up a new Maximo project. The project used for this data file was not built with BIM delivery, so the contractors collected all the information manually after construction and sent the information to the facility management group. This section describes how the contractors can use BIM models to collect information during the design and construction process using a Revit template.

Revit features that can be used to achieve this goal are shared parameters and schedules. These two features can help the designers and contractors collect and provide accurate and up-to-date information about elements in a project model. In this case, mechanical equipment elements are used for the example. When the template is built, it can be used for any project.

Shared parameters are used to add parameters to families or projects that can be shared with other families and projects, which can help maintain consistency across different projects. Shared parameters give the user the ability to add data that is not predefined in the family file or project template. A schedule is used to display information in a tabular form, extracted from the properties of the elements in a project. A schedule can list every instance of the type of element that is being scheduled, or it can collapse multiple instances into a single row, based on the schedule's grouping criteria (Autodesk 2012).

The steps to set up the Revit Template for mechanical equipment are as follows:

- Create a new shared parameter group named “Asset Record”, and create new shared parameters under this new parameter group. In this case, based on the data requirements provided by the studied company, the shared parameters created are listed as shown in Figure 5-11.
- When all the shared parameters are set up, create a new schedule for mechanical equipment. When the new schedule is created, the new parameters created in the previous step are available as shown in Figure 5-12.

After all the required parameters are set up in the new mechanical equipment schedule, for all the elements that are in the mechanical equipment category, new fields are shown for the users to input information during design as shown in Figure 5-13. For example, the VAV box shown in the red circle has more parameters than the default Revit parameters. The user-defined parameters are shown in the red rectangular area. In addition, a new mechanical equipment schedule named “Asset Record” is shown in Figure 5-14. In order to let the users match the asset list with the elements in the model, some parameters predefined in Revit can be used such as “Mark” and “Level” as used in Figure 5-14. An example of the asset record template with information input with corresponding model elements is shown in Figure 5-15. After all these steps, the schedule created can be exported to MS Excel format. If the users have already input all the information into the required field during the design and construction phases, all the information is kept and exported automatically into the MS Excel file so that the contractors do not need to collect information again after completion of construction as in the current practice the company has followed for decades.

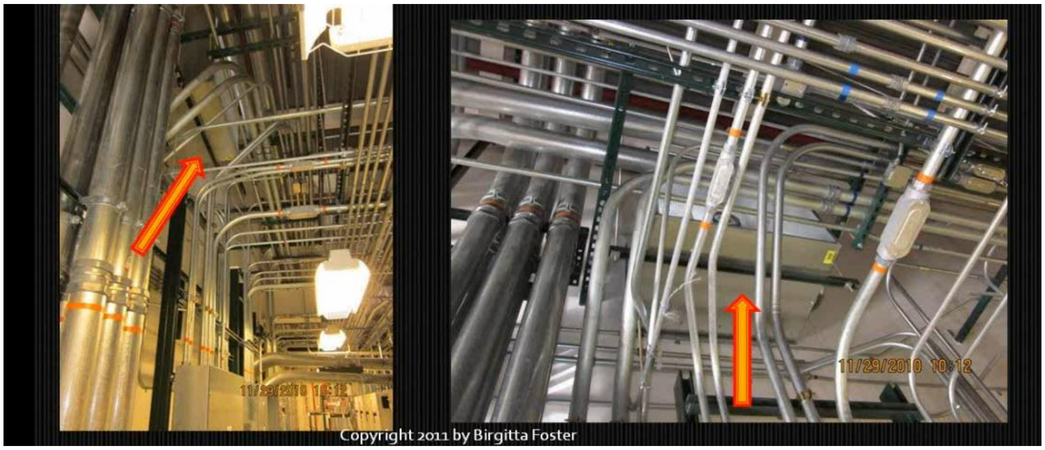

Figure 5-1. Relief fan example (Foster 2011b)

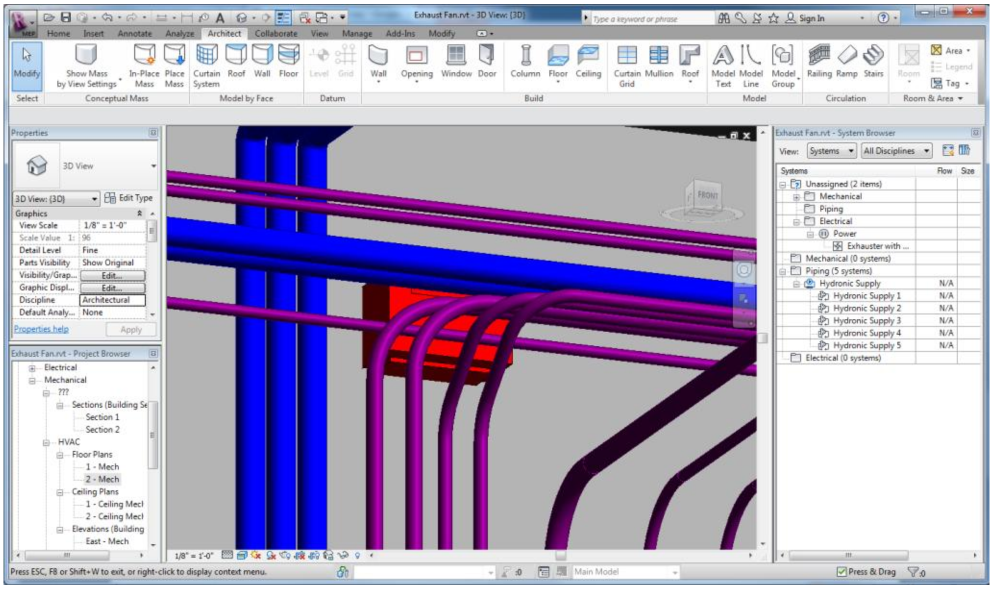

Figure 5-2. Revit Model of Exhaust Fan Scenario

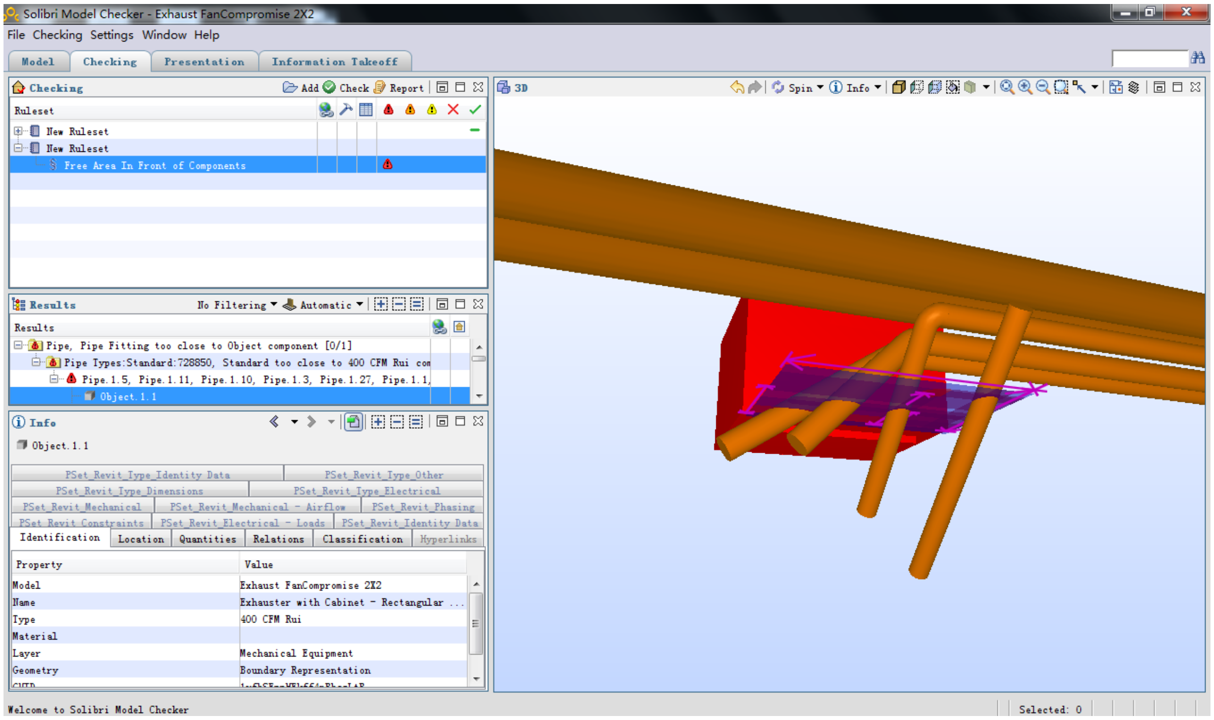

Figure 5-3. Accessibility checking in SMC

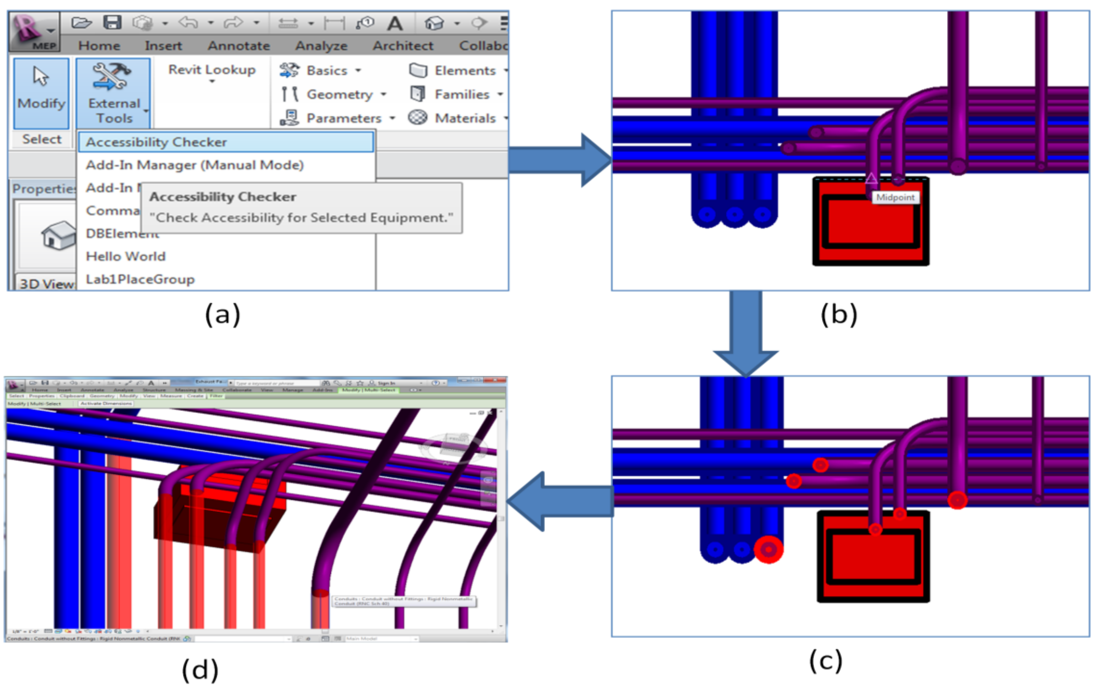

Figure 5-4. Steps for accessibility checking in Revit Accessibility Checker Add-In

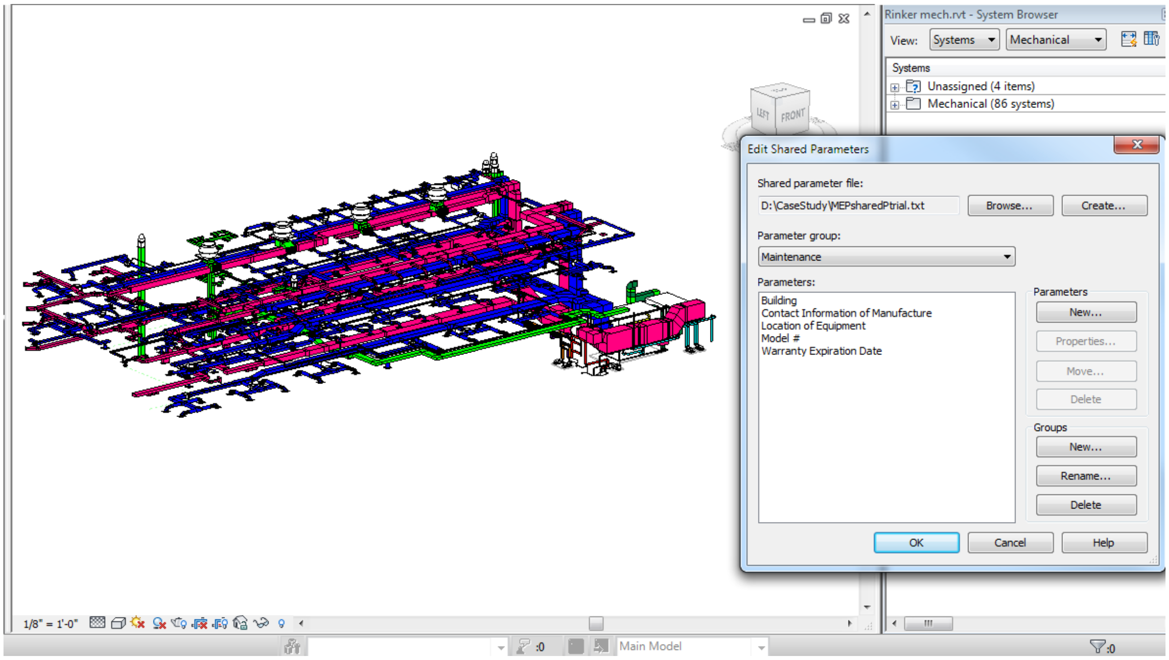

Figure 5-5. MEP model and shared parameters editing

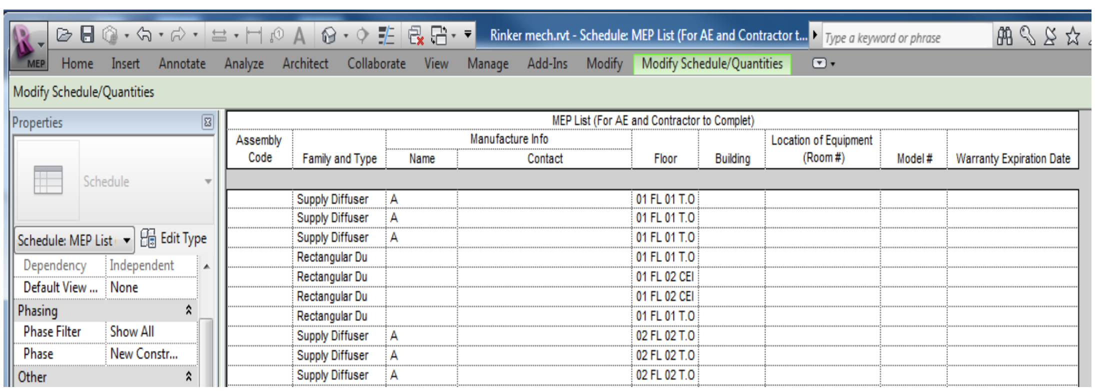

Figure 5-6. MEP list for collecting data in AEC phase

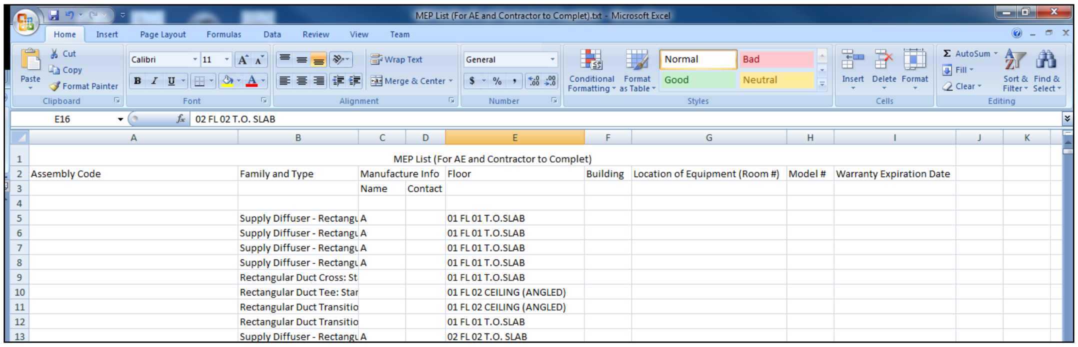

Figure 5-7. MEP list export to excel

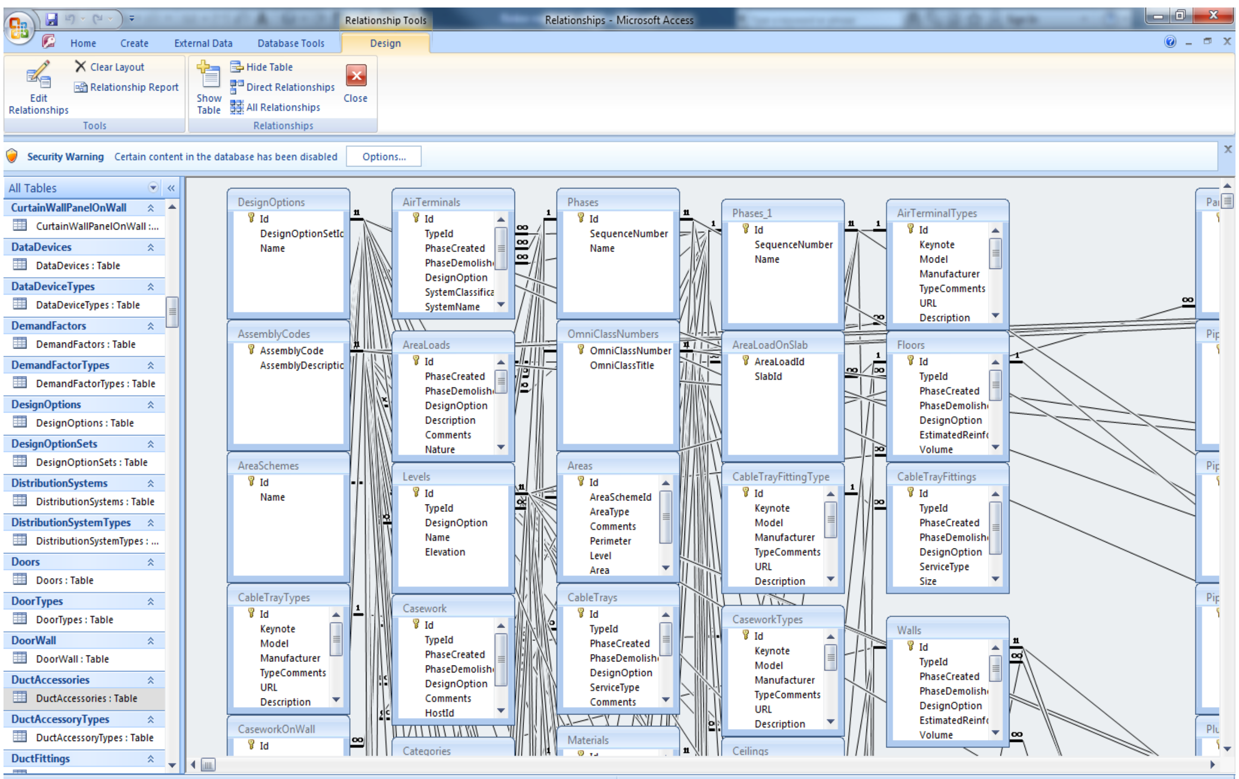

Figure 5-8. Relationships of Revit classes

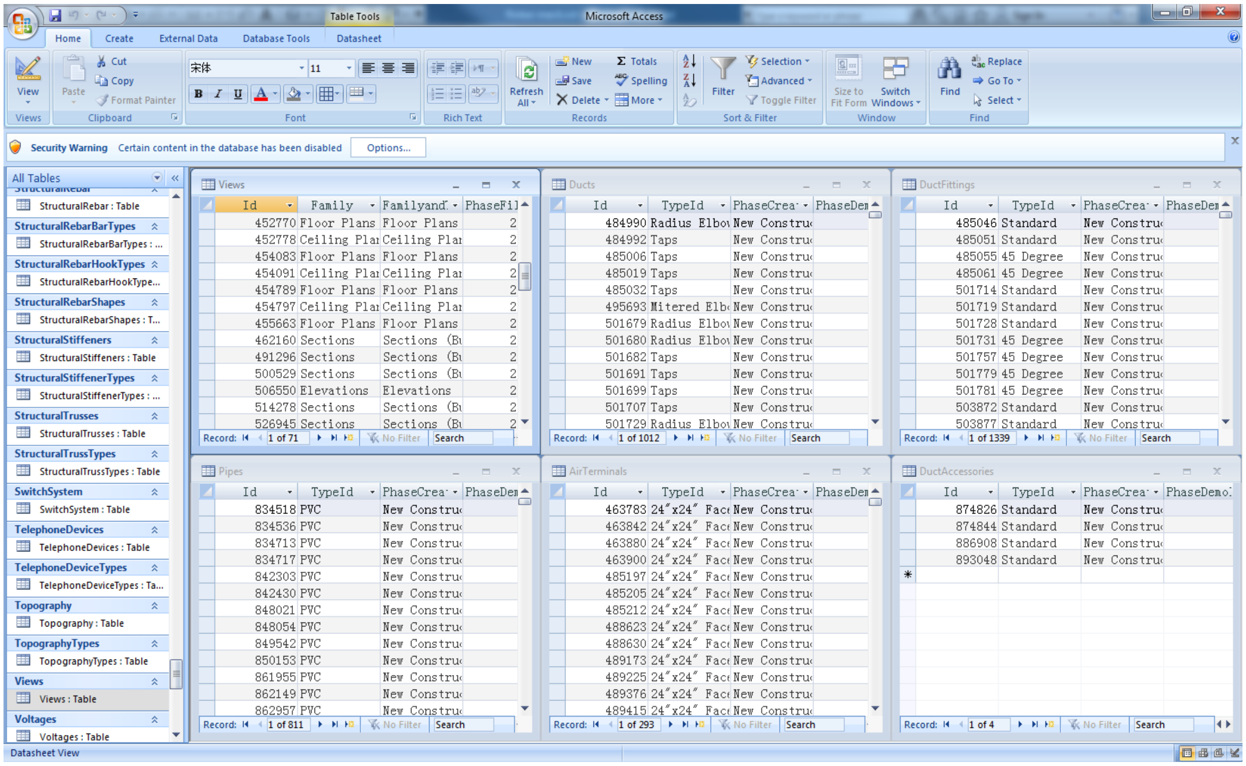

Figure 5-9. Tables in the Revit database

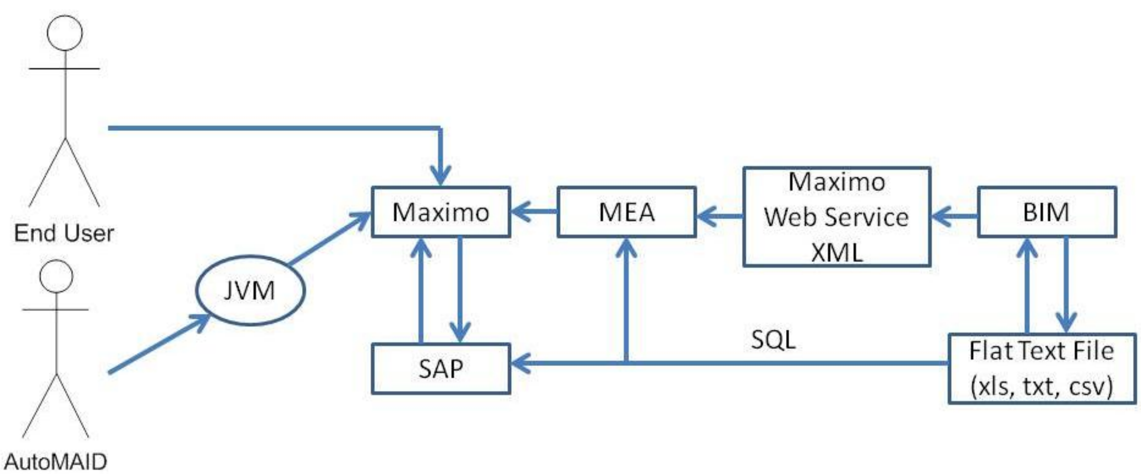

Figure 5-10. Maximo BIM integration working schema

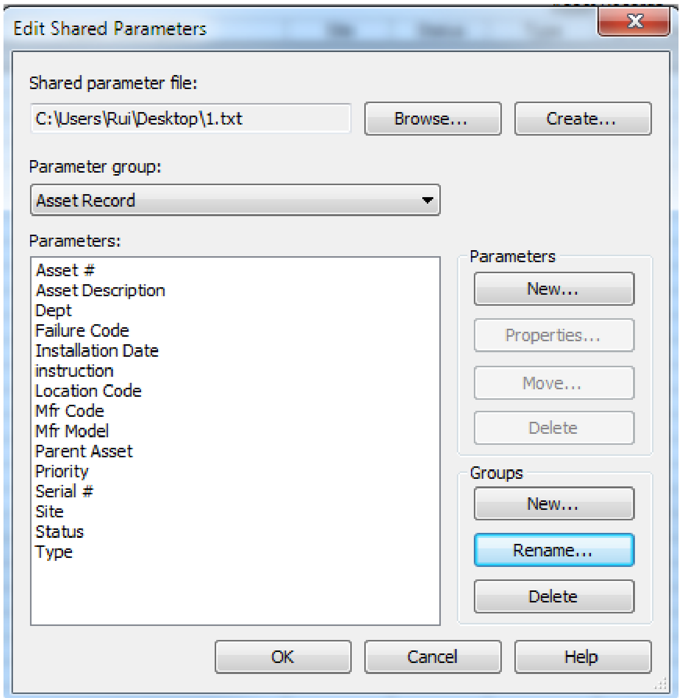

Figure 5-11. Shared parameters set up

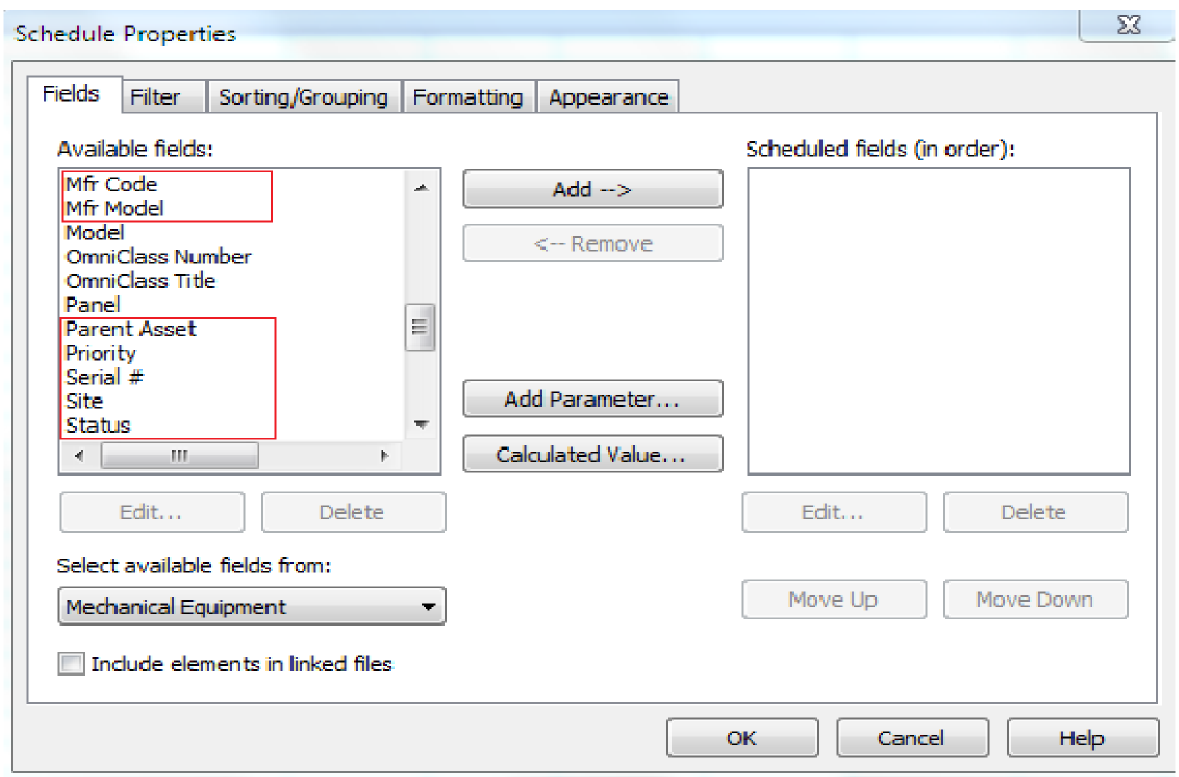

Figure 5-12. Schedule properties showing new parameters

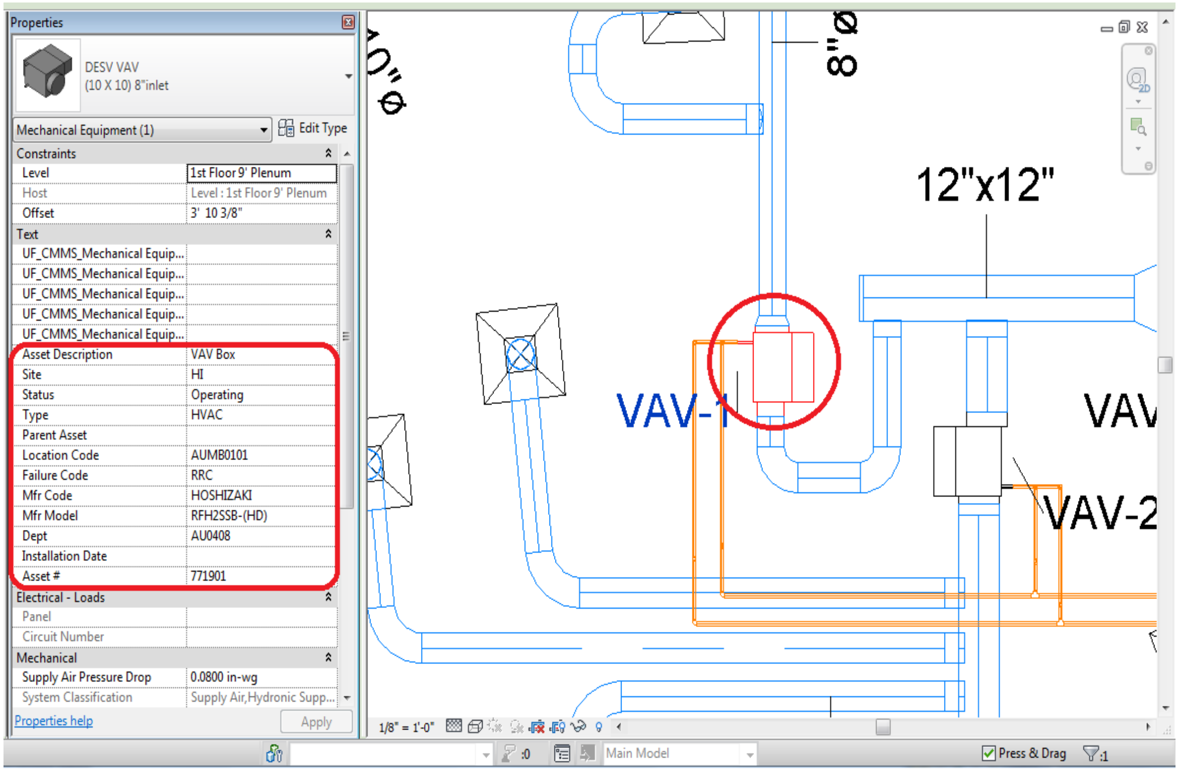

Figure 5-13. Mechanical equipment with new parameter fields

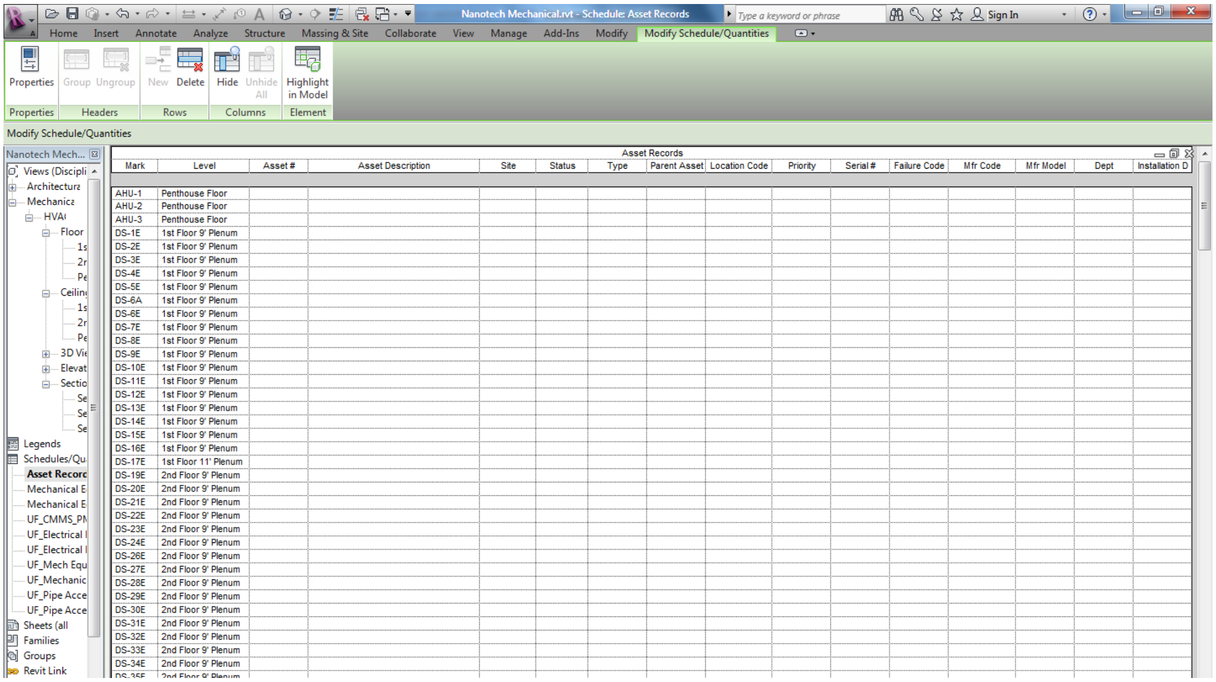

Figure 5-14. New mechanical equipment schedule with new parameters

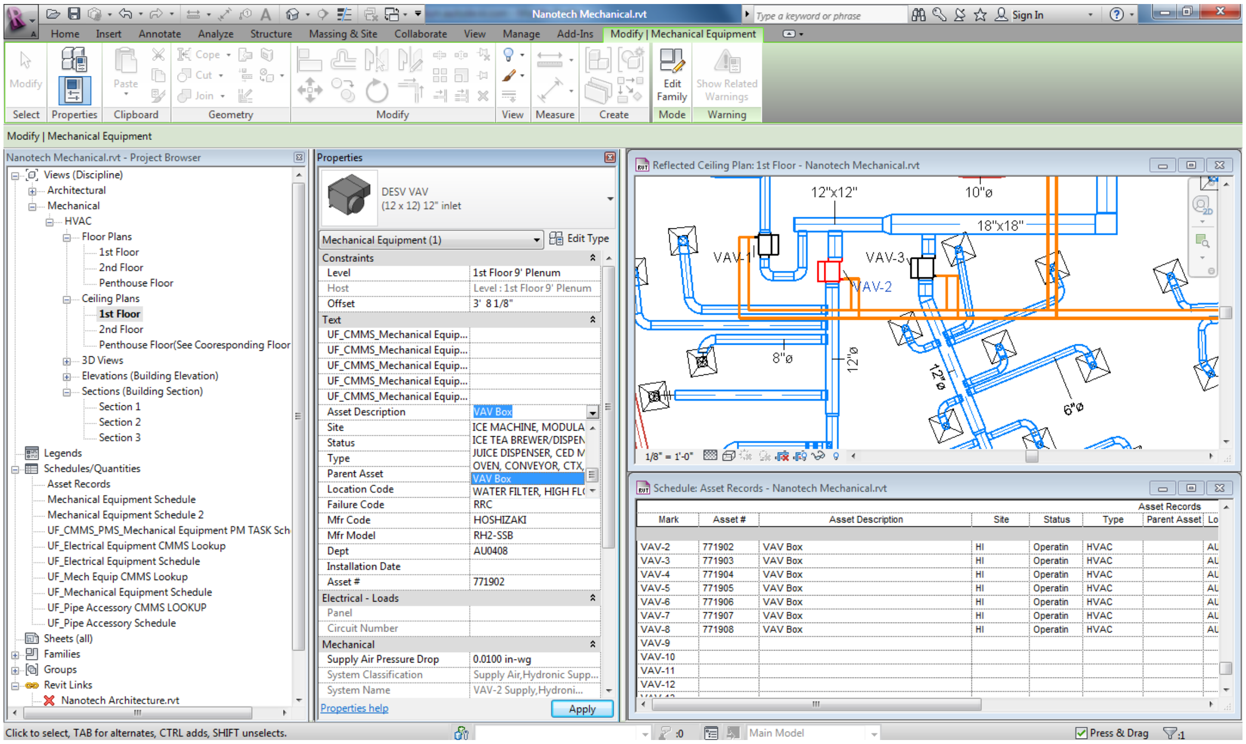

Figure 5-15. An asset record template with information input

CHAPTER 6
CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

Conclusions

BIM has changed the way the AEC industry communicates and cooperates. Knowledge sharing between the facility management and design professionals has become possible with BIM. BIM technology has been used effectively in the design and construction phases. There is a need to expand BIM beyond the design and construction phases and to consider using BIM for facility management such as in maintenance activities. However, the research on BIM use for facility management is lagging behind the study of BIM in design and construction phases. This research investigated the current industry application of BIM for facility management by a questionnaire, developed a Revit Add-In tool that can help designers and engineers check for maintenance accessibility problems in design phase. A case study was used to illustrate and validate the Add-In tool. Additionally, templates in Revit have been built in order to carry information from design and construction phases to facility management phase.

The BIM-assisted facility management survey had no responses from civil Engineers, structural engineers, structure designers and fabricators, MEP subcontractors, MEP manufacturers nor did MEP suppliers respond to this survey, although there were such companies in the pool. The absence of these organizations could be meaningful. First of all, these groups may not have opportunities to get involved in BIM or facility management and perhaps they are not interested or familiar with the topic studied. Secondly, cooperation in the AECO industry is still segmented and different stakeholders are working in their own areas without sharing technology and information with others.

Maintenance costs, although the largest cost over a building's life cycle, are currently rarely considered in the early design phase. Some design errors that make maintenance activities impossible to perform are always hard to visualize in the design phase. As the next advancement for Facility Management (FM), design for maintenance (D4M) should be considered in the early design phase.

This research used different BIM tools to check designs for maintenance accessibility which brought the concept “design for maintenance” into reality. A case study of an exhaust fan accessibility check was conducted in Solibri and Accessibility Checker, a Revit Add-In developed for this study. The results from the case study show that maintainability checking is possible in the design phase using a Revit Add-In. For industry users who have IFC format BIM models, the SMC rule set database should be improved in order to meet the need of checking for maintenance accessibility problems during the design phase. However, even with a completed built rule set database, the interoperability issues still need to be resolved when converting different file formats to the IFC format.

Limitations

The Revit Add-in Accessibility Checker has more flexibility to satisfy the user's requirements. But it requires the user to have some coding experience as it has to be written in C# or VB. The software codes behind this Accessibility Checker command are specific for this case study. For other scenarios, the software codes will have to be changed. A more general and user-friendly Add-In is planned for the future.

The survey conducted in this research has a low response rate (5.48%). The low response rate may lead to biased results since the perspectives from those who choose not to respond to the questionnaire may hold different ideas than those who respond it. The reason for the low response rate may be because of their unfamiliarity with the topics discussed in the questionnaire since BIM users may not be familiar with facility management, and facility managers may not understand the BIM process. As a result, when they get the questionnaire, neither group is interested in responding to it. In addition, the respondents of the survey are mainly from the US. Since facility management practices are very different in Europe and Asia, the results of this study may be different from those conducted in those places. Overseas studies are needed to get a better global understanding of BIM for Facility Management.

Moreover, the survey identified some of the design defects recognized by industry practitioners. However, because of time limitations and the limited sample pool and responses, it is difficult to identify all the design defects that may lead to maintainability issues. It will require a long term effort for the AECO industry to build up the knowledge database needed for D4M.

Recommendations for Future Research

This study is a first effort in bridging the gaps between the design, construction and facility management phases in the AECO industry. There are several areas that need more future research.

First of all, from the survey results, there are a lot of other issues reported by the respondents such as vandalism, commissioning, auditing, and lack of guidelines for owners, legal problems, which need further study and which are important for realizing the cooperation and sharing of information among different parties of AECO projects.

These problems are not covered in this study but are definitely worth addressing in the future research.

Secondly, the accessibility checker tool developed in Chapter 5 is for a specific scenario. For other scenarios, the software codes have to be changed. A more general and easy to use Add-In will be the future direction of the authors' study.

Thirdly, the design defects that are not maintenance friendly need to be collected from the facility management phase in order to avoid similar design problems in future projects. The problem identified in this research is only the tip of the iceberg. A comprehensive non-maintenance friendly design database needs to be built and made available to the designers.

Additionally, the manufactures should get involved in building the BIM libraries. Although the MEP manufacturers are already involved in some of the BIM equipment library, there is no accessibility requirement in the library. When the BIM end users load the family into their project, the needed space and location of maintenance equipment are not reported. . To improve the current situation, the manufacturers need to set the accessibility box for the equipment in their library, so that, when the end users place the elements from their library in their designs, maintenance equipment accessibility is mandatory. The designers do not need to worry about the specific requirement of the elements they place since it has been set by the manufacturers already. Since different types of equipment have different accessibility requirements, more cooperation is needed with the manufacturers to develop the equipment library with accessibility requirements. When using equipment included in the library, the designer can then be warned about whether there is enough space around it without using the Revit Add-in

Accessibility Checker for each of the objects, which would be more efficient and cost effective.

Finally, this research focused on the technology part of the problem. In the real world, cooperation is necessary among the different parties in the AECO industry to achieve the optimized project with the lowest life cycle cost. Researchers and practitioners should take into consideration the legal documents needed to regulate the responsibilities, risks and cooperation methods between different parties on projects with a common goal to achieve optimized results.

APPENDIX A
BIM-ASSISTED FACILITY MANAGEMENT SURVEY

Instructions:

This survey is designed to assess the Building Information Modeling (BIM) implementation in the Operation and Maintenance phase of a building's life cycle. It is designed to evaluate how BIM is being used post-construction and whether Operations and Maintenance factors are considered early on in the design and construction process.

All of the information collected will remain confidential. Anonymous answers will be used for research purposes only. Thank you for your participation!

PART I – Demographic Information

1. Which of the following best describe your organization in the AECO industry?
   - ❍ Architect
   - ❍ Civil Engineer
   - ❍ Structural Engineer
   - ❍ Construction Manager
   - ❍ Structure Steel Designer
   - ❍ Structure Fabricator
   - ❍ MEP Subcontractor
   - ❍ Consultant
   - ❍ MEP Manufacturer
   - ❍ MEP Supplier
   - ❍ Higher Education
   - ❍ Owner
   - ❍ General Contractor
   - ❍ Facility Manager
   - ❍ Other, please specify

   ....

2. Which of the following best describes your role in your company?

   - ❍ Architect
   - ❍ Engineer
   - ❍ Intern
   - ❍ Project Manager or Project Engineer
   - ❍ Facility Manager
   - ❍ Maintenance Related Staff
   - ❍ Upper Management
   - ❍ Other, please specify

   ....

3. Which segment of the construction market is your organization primarily involved in?

- ❍ Public
- ❍ Health Care
- ❍ Education
- ❍ Private
- ❍ Infrastructure
- ❍ Commercial
- ❍ Residential
- ❍ Other, please specify

4. In the past 12 months, how many new projects were your organization involved in?

5. Among those projects, how many of them utilized Building Information Modeling (BIM)?

6. How would you define your personal BIM experience level?

- ❍ Expert
- ❍ Advanced User
- ❍ Intermediate User
- ❍ Beginner
- ❍ No Experience

7. In order to receive feedback on this study findings, please list your email address:

PART II: BIM-ASSISTED OPERATIONS AND MAINTENANCE

8. During design and construction, is maintainability taken into consideration?
   - ❍ In the design phase
   - ❍ In the construction phase
   - ❍ Both phases
   - ❍ Not considered

9. On most projects, are Facility Management (FM) personnel included in the design and / or construction phases?

   - ❍ FM are involved in the design phase
   - ❍ FM are involved in the construction phase
   - ❍ FM are involved in both phase
   - ❍ No involvement
   - ❍ I do not know

10. If facility management personnel are included in these phases, how do they express their requirements for equipment maintenance?

   - ❍ Some general guidelines
   - ❍ Specific requirements i.e. dimensions and space requirements for equipment accessibility
   - ❍ Not applicable
   - ❍ Other specific requirements, please specify

   ....

11. In your experience, have manufacturers and / or suppliers provided adequate information regarding equipment maintainability for future maintenance activities?

   - ❍ Adequate information
   - ❍ Some information
   - ❍ No information
   - ❍ Other, please specify

   ....

12. In what format is O&M information regarding MEP maintenance usurally required by your organization? Select all that apply:

   - ❑ A physical paper copy
   - ❑ A digital copy on a CD or DVD
   - ❑ BIM with specification information attached (i.e. a model and COBie spreadsheet)
   - ❑ A BIM integrated into some form of computerized maintenance management system (CMMS)
   - ❑ Other, please specify

   ....

13. Please list the top three maintenance headaches. (Specific description of each situation. If possible, please provide the corresponding picture of the situation.)

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14. Please rank the following MEP maintainability problems based on frequency.

	Never	25% of the time	50% of the time	75% of the time	100% of the time	N/A
Lack of equipment accessibility	1	2	3	4	5	N/A
Please give specific descriptions of the above problem that you have experienced						
Poor design of equipment layout	1	2	3	4	5	N/A
Please give specific descriptions of the above problem that you have experienced						
Lack of adequate space for mechanical room	1	2	3	4	5	N/A
Please give specific descriptions of the above problem that you have experienced						
Limited space for AHU filter access	1	2	3	4	5	N/A
Please give specific descriptions of the above problem that you have experienced						
Other problems, please list below	1	2	3	4	5	N/A
Please give specific descriptions of the above problem that you have experienced						

15. Does your organization assess MEP maintainability in the design phase of most projects? If so, how?

16. Does your organization assess MEP maintainability in the construction phase of most projects? If so, how?

17. Does your organization assess MEP maintainability in the operation phase of most projects? If so, how?

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18. In the operation and maitenance phase, if a part of the design leads to maintenance problems, how is the situation resolved? (e.g. It is found that there is no access space to service a component of an MEP system)

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19. What is the existing Facility Management Management System software that you are using?

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20. When you utilize your work order system, does it currently provide the information needed to complet the work?

- ❍ Yes
- ❍ No
- ❍ Please explain your answer

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21. Are you using a BIM model for Facility Operation and Maintenance? If so, how?

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22. If a BIM model is in use, does it have enough information for Facility Operation and Maintenance purpose?

- ❍ It carries enough information for Facility Operation and Maintenance
- ❍ It carries part of the information needed for O&M, manually input is required
- ❍ It carries no information needed for O&M, all the information for O&M is entered manually
- ❍ Other, please specify

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23. What work order information is needed if equipment requres repair? Select all that apply:
    - ❑ Name of Manufacturer
    - ❑ Contact Information of Manufacturer
    - ❑ Location of the equipment
    - ❑ Down time
    - ❑ Equipment model Number
    - ❑ Cut Sheet
    - ❑ O&M Repair Instruction
    - ❑ Other, please specify

    ....

24. Have you had any uncompleted work orders? If so, what were the reasons for these uncompleted work orders?

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25. What information is needed for Facility Operation and Maintenance that is typically hard to locate?

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26. Based on your personal experience, should maintainability be considered in the design and / or construction phases?

    - ❑ Yes
    - ❑ No
    - ❑ Please explain your answer

    ....

27. If you work in the Facility Management phase, are there any suggestions that you want to make to the designer for better maintainability?

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28. If you have any other comments you would like to share, please use the space provided below. Thanks for your participation!

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APPENDIX B
BIM-ASSISTED FACILITY MANAGEMENT SURVEY-CODE BOOK

Table B-1. BIM-assisted facility management survey-code book

Question Number	Variable	SPSS variable name	Coding Instruction
0	Identification number	ID	Number assigned to each Survey(Each respondent has one unique number)
1	Organization	Org	1 Architect 2 Construction Manager 3 Consultant 4 Higher Education 5 Owner 6 General Contractor 7 Facility Manager 8 Software Developer 9 Design Builder 99 Other
2	Personal Role in Company	Role	1 Architect 2 Project Manager/Project Engineer 3 Facility Manager 4 Upper Management 99 Other
3	Construction Market Segment	Seg	1 Public 2 Health Care 3 Education 4 Private 5 Commercial 6 Residential 99 Other
4	Last year new projects	NewProj	Number of New Projects
5	BIM projects	BIMProj	Number of Projects

Table B-1. Continued

Question Number	Variable	SPSS variable name	Coding Instruction
6	Personal BIM Experience Level	BIMLevel	1 Expert 2 Advanced User 3 Intermediate User 4 Beginner 5 No Experience
8	Maintainability taken into consideration?	MStatus	1 In the design phase 2 In the construction phase 3 Both Phases 4 Not Considered
9	FM personnel involvement	FMInvlv	1 FM involved in design phase 2 FM involved in construction phase 3 FM involved in both phase 4 No involvement 5 I do not know
10	How FM express their requirement for maintenance	RqrExpr	1 Some general guidelines 2 Specific Requirements i.e. Dimensions and space requirements for equipment accessibility 3 Not applicable 4 Other specific requirements, please specify
11	Adequate information regarding equipment maintainability for future maintenance activities	MntInfo	1 Adequate information 2 Some information 3 No information 99 Others
12	OM information delivery format	OMFmtPaper OMFmtCD OMFmtBIM OMFmtBIMCM	1 Yes 2 No

Table B-1. Continued

Question Number	Variable	SPSS variable name	Coding Instruction	
13	Information Accessibility	InfoAccs	1	Yes
	Poor As-built document	PrAbDoc	0	No
	Information Accuracy	InfoAcrcy		
	Accessibility/Clearance Issues	AccClr		
	Budget/cost	Cost		
	Software interoperability	SWIntp		
	Lack of trained personnel(including BIM and CMMS)	LckPrs		
	Lack of preventative maintenance	LckPM		
	Cooperation and trust between parties	Trust		
	Others	OtherHdch		
14	Lack of equipment accessibility	EqpAccs	1	Never
	Poor design of equipment layout	PoorLayout	2	25% of the time
	Lack of space for mechanical room	SpcLack	3	50% of the time
	Lack of space designed in the ceiling	SpcCeil	4	75% of the time
	Limited Space for AHU filter access	SpcFilter	5	100% of the time
	Other Problem		99	N/A
15	Assess MEP maintainability in design phase	DsgnMnt	1	Yes
			2	No
			3	Sometimes, depends on requirements
			4	Tried but failed
			99	Others
16	Assess MEP maintainability in construction phase	ConstMnt	1	Yes
			2	No
			3	Sometimes, depends on requirements
			4	Tried but failed
			99	Others

Table B-1. Continued

Question Number	Variable	SPSS variable name	Coding Instruction
17	Assess MEP maintainability in operation phase	OprMnt	1 Yes 2 No 3 Sometimes, depends on requirements 4 Yes, but too late 99 Others
20	Work Order Information enough?	WOInfo	1 Yes 2 No 99 Others
21	Using BIM for FM	BIM4FM	1 Yes 2 Start to 3 No 99 N/A
22	enough info from BIM to OM	BIMinfo	1 Enough 2 Some 3 No info 99 Others
24	Uncompleted Work Order	UnCmpltWO	1 Yes 2 No 99 N/A
26	Maintainability taken into Design and Construction phase	DCM	1 Yes 2 No

APPENDIX C
MAINTENANCE HEADACHES RESPONSES

13. Please list the top three maintenance headaches. (Specific description of each situation. If possible, please provide the corresponding picture of the situation.)

Case #	Response
1	software changes make system given to read documents out of date direct links to drawing objects that link to the we become dated and not supported by vendor lack of training for maintenance people in using the software after the contractor leaves the site and new staff are hired
2	Clearance Issues Lack Of information Cumbersome information access
4	Vandalism - repainting Occupier wear and tear- misuse Equipment usage
5	Learning a new building Finding info on new building equipment Storing equipment information
6	visibility to work performed, accountability of the vendor, accurate reporting of work performed, vendor performance, FCI, budget to actual, etc.
7	Poor As-builts, Short PM work windows- park open approx. 12 to 15 hours daily 365 days Ride systems control's
8	Not sure.
9	1) as-built drawings not correct i.e. when we have an issue, the drawings are generally not correct - such as needing location of breaker 2) equipment too close so difficult to maintain 3) duct/smoke detectors in areas that can't maintain
11	air handlers chillers roof
12	lack of or inaccurate asbuilts accessibility to building equipment improper design in building systems
14	1-API (application program interface) which is not open. Attitudes of not sharing data between systems must change. 2-No standards developed specific for owners to follow (FM association standards with regard to BIM) 3- No clear guidance to owners about where immediate value is; ie it takes work, so to do it, they need to be made aware of the reasons why (educations is needed)
17	Access to equipment. Valves that are mounted in hard to reach places. Lack of full coordination among designers / trades leaves one system in the way of another etc. Access to information about facility. Especially consistency from project to project. Equipment that does not meet spec. Cost constraints driving decisions in construction or substitutions that do not fully integrate.
19	insufficient space to remove/reinstall the object inadequate isolation/shut-off valves in access to power/control back boxes
20	1. Getting accurate information regarding the products installed 2. Building an accurate inventory of assets 3. Planning maintenance for those assets
22	accessibility clearances Commissioning test ports Measurement and verification

	systems for auditing
24	Link between paper copy and actual equipment
25	1. Variance between recommended and actual practice 2. Vagueness of expected service life information 3. Poor classification
26	information lack of knowledge and expertise on specific items no integration of systems detailed
27	As a contractor, our main headache is training personnel, then those trained change positions or no longer work for the owner.
28	Lack of electronic O&M. Primarily a contractual issue that needs to be resolved. Immature BIM knowledge by project managers which limits our ability to use BIM in FM. Slow cultural change (but it is happening).
31	Access and Tracking
32	Dependability of HVAC systems. Corrosion of aged pipes (cause not yet determined). Cleanability of finishes.
34	lack of pm lack of instructions for equipment maintenance, not enough budget or understanding at upper levels as to the need for pm
35	cross referencing plans and spec information, lack of information on older facilities, lack of accurate as-built information.
36	Bad data from Project Delivery Funding when needed is not available ALL data not avaialable when needed
37	HVAC Controls "Water" leaks Appearance/ maintainability of floors
38	Inadequate as-built systems data/documents. Doors and Hardware malfunctions. Deferred maintenance troubleshooting.[1]

[1] Note: The above list is typed by the respondents; typos are shown exactly as the input.

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BIOGRAPHICAL SKETCH

Rui Liu received her Bachelor of Management degree in construction management and Bachelor of Science in applied mathematics at Tianjin University in June 2005. She completed her Master of Management degree in project management at Tianjin University in June 2007. She earned her Master of Science degree in information systems and operations management from The Warrington College of Business Administration at the University of Florida in 2010. She completed her Doctor of Philosophy in design construction and planning at the University of Florida in summer 2012. She would like to continue her career in Academia.

Rui Liu got married to Jun Zhang in 2007 and they are raising two kids Daniel Zhang and Jason Zhang together in Florida. The whole family is excited and ready for the coming adventures in their life.