Building Information Modeling Based Integration and Visualization for Facilities Management

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complied with the regulations of the University and meets with the accepted standards with respect to originality and quality.

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ABSTRACT

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Yoosef Asen

Facilities managers need to identify and understand deterioration/failure causes-effect patterns in order to prepare preventive maintenance plans. However, this task is difficult because of the complex interaction between different building components and their operational conditions. In spite of the availability of advanced Computerized Maintenance Management Systems (CMMSs), these systems focus on the data management aspects (i.e. asset inventory, work orders and resource management) and lack the functions necessary to analyze the collected data in order to identify deterioration/failure patterns. Standardization based on Building Information Modeling (BIM) provides new opportunities to improve the efficiency of Facilities Management (FM) by sharing and exchanging building information between different applications throughout the lifecycle of the facilities. This research proposes the integration of FM related data from different sources such as CMMS and BIM through adding the CMMS inspection and maintenance data to the BIM database. This integration, in addition to defined logical and spatial relationships between components and spaces, is used to find the cause-effect relationships through a BIM-based visual analytics. This method facilitates heuristic problem solving and helps to increase the quality of O&M phase. It is

also proposed to integrate CMMS, BIM, video, and Real Time Location System (RTLS) data using Augmented Reality (AR) techniques to visualize construction and renovation operations and to retrieve information about the time, space, and related activities to visualize construction and renovation operations. Several case studies are implemented and tested to show the feasibility of the proposed methods.

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DEDICATION

To my father, mother, sister, and brothers who made all of this possible, for their endless encouragement and support.

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LIST OF ABREVIATIONS

Abbreviation	Description
3D	Three-dimensional
4D	Four-dimensional
AECOO	Architecture, Engineering, Construction, Owners, and Operators
AHU	Air Handling Unit
API	Application Programming Interface
BIM	Building Information Model
CAD	Computer-Aided Design
CMMS	Computerized Maintenance Management System
COBIE	Construction-Operations Building Information Exchange
FM	Facilities Management
IAI	International Alliance of Interoperability
IDM	Information Delivery Manual
HVAC	Heating, Ventilation and Air Conditioning
IFC	Industry Foundation Classes
IFC-mBomb	IFC Model Based Operation and Maintenance of Buildings
MM	Maintenance and Management
MVD	Model View Definition

NIBS	National Institute of Building Sciences
NBIMS	National Building Information Model Standard
O&M	Operation and Maintenance
STEP	STandard for the Exchange of Product model data

CHAPTER 1 INTRODUCTION

1.1 General

The Architecture, Engineering, Construction, Owners, and Operators (AECOO) industry is a fragmented industry which comprises different stakeholders and needs a lot of coordination between these parties. Accordingly, this issue has caused some barriers in communication between the parties which leads to a decreased efficiency. Building Information Modeling (BIM) as an emerging concept is expected to solve the lack of interoperability between software by sharing the information through the facilities lifecycle (Underwood and Isikdag, 2009). "A Building Information Model is a digital representation of physical and functional characteristics of a facility" (WBDG, 2011).

Facilities managers need to identify and understand deterioration/failure cause-effect patterns in order to prepare preventive maintenance plans. However, this task is difficult because of the complex interaction between different building components and their operational conditions. In spite of the availability of advanced Computerized Maintenance Management Systems (CMMS), such as Maximo (Maximo, 2011) and FM:Interact (FMSystems, 2011), these systems focus on data management aspects (i.e. asset inventory, repair orders and recourse management) and lack the functions necessary to analyze the collected data in order to identify deterioration/failure patterns. Decisions on maintenance-related works usually are made based on various types of accumulated historical data, such as design drawings, inspection records, sensing data, etc. (Chen and Wang, 2009). Most of these data are text-based which makes it time-consuming and less intuitive for correlating information. Furthermore, inspection history data are not always available for some components, which makes the above task even more difficult. According to Akcamete et al. (2009), storing the history of facilities' changes is beneficial as facility managers can utilize the historical data of changes for prioritizing maintenance decisions.

Standardization based on BIM provides new opportunities to improve the efficiency of Facilities Management (FM) by sharing and exchanging building information between different applications throughout the lifecycle of the facilities. BIM 3D data can be used in the CMMS where the inspection and maintenance data can be added to the database. The integration of CMMS and BIM data can be used for visualization which can facilitate heuristic problem solving and provide an opportunity for visual analytics. Furthermore, Construction-Operations Building Information Exchange (COBIE) has been developed as another effort towards standardization of FM required data handover by the contractor to the owner at the end of commissioning phase (WBDG, 2011).

Several methods can be used to model the information of O&M processes and to monitor the execution progress of these processes. Among these methods, Building Information Modeling (BIM), video recording, and location tracking of construction resources have been extensively studied in recent Augmented Reality (AR) research. BIM allows to model the components of a building in 3D and to visualize the sequence of the construction processes by linking the schedule information to the 3D model, resulting in a 4D visual simulation (4D BIM, 2011). Video monitoring has been used to record and monitor construction activities for the purposes of claim resolution and for studying the overall performance of the construction project using time-lapse photography (Abeid and Arditi, 2002; Chae and Kano, 2007). Location tracking of construction resources has been suggested as an effective method for progress monitoring (Navon and Sacks, 2007). More recently, location tracking of resources has been proposed by several researchers to capture deviations from the schedule or other changes in the project. Several technologies have been investigated for location tracking including the Global Positioning System (GPS) (Riaz et al., 2006), Radio Frequency Identification (RFID) (Chae and Yoshida, 2008), and Ultra-Wideband (UWB) Real Time Location Systems (RTLS) (Cho et al., 2010).

Each of the above automated methods (e.g. video and RTLS) can provide useful information about the construction processes and has certain advantages and disadvantages. Video monitoring provides a rich visual source of information that can be used by a human observer or can be automatically processed to extract features using video processing techniques (Chae and Kano, 2007). However, processing the video contents is complex and has several limitations (e.g. video occlusion) and does not identify individual workers captured in the video. RTLSs, on the other hand, can identify the individual construction resources (workers, equipment and materials) and their locations over time. However, they do not provide the contextual information about the actual work performed using these resources. Therefore, video and RTLS can also be integrated with BIM and be used to provide better understanding of the progress of construction and renovation operations.

1.2 RESEARCH OBJECTIVES

This research work elaborates on the usage of BIM as an emerging and beneficial technology in FM in order to improve the O&M in addition to construction and renovation operations of facilities in terms of cost, time, and quality.

The objectives of this research are: (1) to review current research on the application of BIM in FM and the current status in the practice; (2) to investigate the technical feasibility of integrating COBIE related data with CMMS and BIM; (3) to investigate the feasibility of integrating BIM with CMMS for BIM-based visual analytics to identify potential deterioration/failure and cause-effect relationships; and (4) to identify the potential benefits of integrating BIM, video monitoring, and RTLS in an AR application for visualizing construction and renovation operations.

1.3 THESIS ORGANIZATION

This study will be presented as follows:

Chapter 2 Literature Review: In this chapter, the applications of BIM technology in FM, specifically in terms of integration and visualization, are reviewed. COBIE as a new standard for data handover at commissioning phase and its benefits in comparison with the traditional way of handover is reviewed. Other topics such as Industry Foundation Classes (IFC), databases, and FM software interoperable with BIM are covered in this chapter. This chapter also covers the AR applications in the construction phase, in addition to location tracking using Ultra Wideband (UWB) technology.

Chapter 3 Visual Analytics in FM: In this chapter the procedure of integrating CMMS with BIM and then 4D simulator, is explained. This chapter also includes the method of using queries for visual analytics of cause-effect relationships between components and spaces. The steps of integrating COBIE with BIM also are covered in this chapter. A case study is also implemented to prove the validity of the proposed approach.

Chapter 4 Augmented Reality Based Visualization of Construction and Renovation Operations: This chapter proposes a new approach based on AR to visually fuse the data from different sources including a BIM, video monitoring, and an Ultra Wide-Band (UWB) RTLS. The proposed method shows the use of visualization in construction and renovation operations and to retrieve information about the time, space, and activities. A case study about BIM-based visualization of progress monitoring of construction and renovation operations is tested to demonstrate the feasibility of the proposed method.

Chapter 5 Conclusions and Future Work: This chapter includes the summary of the present research work, highlights its contributions, explains the limitations and proposes the recommendations for future works.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, BIM technology in the AECOO industry and the benefits of its usage for FM are reviewed. The literature review starts with BIM technology definition and IFC as the most accepted format and standardized BIM. Then, COBIE as a new standard for FM required data delivery is explained and elaborated. FM and its related tools in terms of compatibility with BIM are also covered in this chapter. The current status of BIM application for FM, integration and visualization of FM data, cause-effect relationships between components, and visual analytics of such relationships are reviewed in this chapter. In addition, Augmented Reality (AR) and data fusion, location tracking using Ultra WideBand(UWB) technology, and databases are reviewed in this chapter as well.

Based on search in ProQuest Dissertations & Theses (PQDT), it was found that there are about forty doctoral dissertations and masters theses related to BIM. Out of these forty researches, only three studies where related to FM (PQDT, 2012).

2.2 BUILDING INFORMATION MODELING (BIM)

The AECOO industry is a dynamic, complex, and fragmented industry. According to a study made by the US Bureau of Labor Statistics, all industries have had an increase in productivity by over 200% since 1964. During this period, the AECOO industry has had a decreasing rate in productivity (AIA, 2007). Traditionally, there is a gap between the design and construction disciplines of this industry because the designers and contractors hardly communicate before the start of the construction phase. The lack of construction information in the design phase results in the decrease of quality, and increase of time and cost of the projects. According to the National Institute of Standards and Technology (NIST), the lack of interoperability in the software in the AECOO industry costs $15.8 Billion annually (Uhlik and Lores, 1998). Using FM-related information during the earlier phases can also increase the performance efficiency of the facilities.

BIM is an emerging technology that helps all stakeholders work together, which leads to an increased efficiency. Figure 2-1 (a) shows the document centric approach, which has several challenges for information sharing, and Figure 2-1 (b) shows the centric information approach. According to Sjogren and Kvarsvik (2007) the main issues with the document centric approach are: (1) communication errors and loss of project information within the same domain, and (2) re-entering information on average seven times in different systems before the delivery of the facility to the owner. In the centric information approach, all the stakeholders are able to communicate to each other through a common language by using BIM technology and use a single repository for all the information (Sjogren and Kvarsvik, 2007). BIM helps to create and use coordinated, consistent, and computable information about a building project. In addition, the parametric nature of this information helps in design decision making, production of high-quality construction documents, prediction of building performance, cost estimating, and construction planning (Eastman et al., 2011). BIM can also be used in renovation or demolition work (Becerik-Gerber et al., 2011). Motamedi and Hammad (2009) studied the lifecycle management of facilities components using RFID and BIM.

BIM is a rich model as all the components in BIM have properties and relationships which help for making queries or doing simulation using the model data (Mitchell and Schevers, 2005). According to Mitchell and Schevers (2005), robust geometry, comprehensive and extensible object properties, semantic richness, integrated information, and lifecycle support can be considered as generic attributes of a BIM. BIM is not just using design technologies to display all the building components in a virtual environment or in a 3D representation. BIM can be considered as a transformation of the traditional design delivery process to a more integrated one (Eastman et al., 2011).

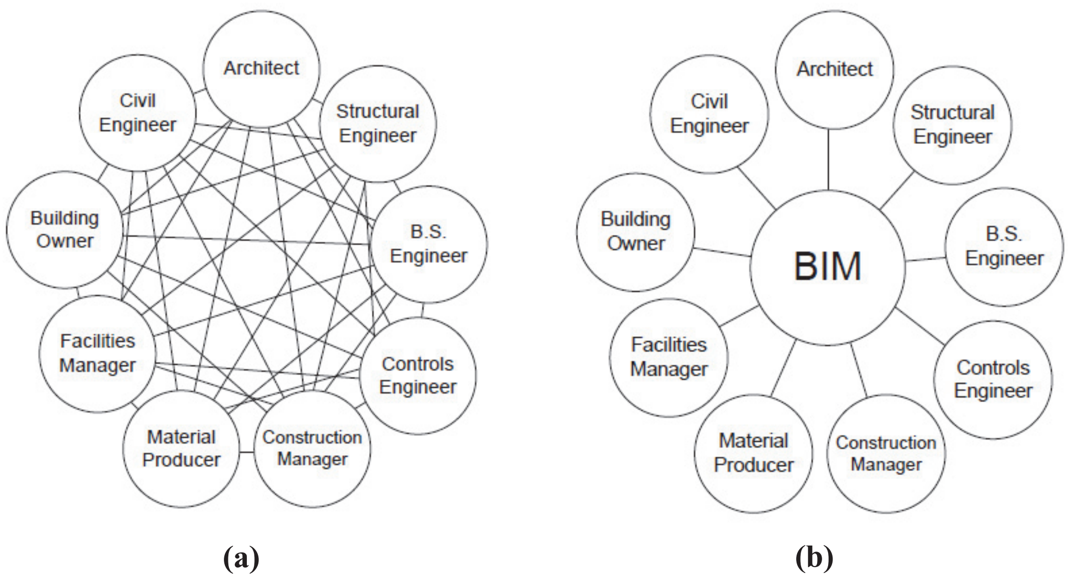


Figure 2-1 (a) Document Centric vs. (b) Information Centric Approaches (Sjogren and Kvarsvik, 2007)

The AECOO industry has been changed over the last decades, and buildings have become more complex with more integrated systems which are interconnected. Therefore, as buildings are getting much more complex, designer should consider more factors in the analysis of their designs. BIM makes it possible to have one repository to store all the design components' data and each component should be described once. BIM provides both graphical and non-graphical data such as drawings, specifications, and schedule. Changes to each item should be done only once and in one place, so all the team members can monitor the changes instantly. One of the benefits of BIM is that BIM makes it possible for all stakeholders to insert, extract, and modify information of the building during the different phases of the facility lifecycle. By using BIM, a 3D simulation of the building and its components can be realized. This helps to predict collisions and to calculate material quantities (Eastman et al., 2011). According to Khemlani (2004), in earlier Computer Aided Design (CAD) systems, building components such as walls, doors, and windows were represented by using geometric entities such as points, lines, rectangles, planes, etc. (Figure 2-2 (a)). BIM-based CAD systems are object oriented in that basic components of drawings are building elements. Furthermore, in traditional 2D and 3D CAD systems, space is not defined explicitly, but in building data model, space is a fundamental part of the building data model that can define the relationships between walls, ceilings, and floors. Figure 2-2 (b) shows the wall-to-space relationship in a building data model. It is also possible to do several types of analysis relevant to the spaces by using BIM, which is not possible by the use of traditional CAD systems.

As shown in Figure 2-3, BIM can be used during the whole lifecycle of a facility from the design phase to the demolition. O&M, guaranties, and other FM-related information can be covered by BIM. By using BIM, Information would be transferred from one phase to the next one. This kind of data flow increases the quality and integrity of information transmission and avoids unnecessary reworks of information management (BuildingSMART, 2011).

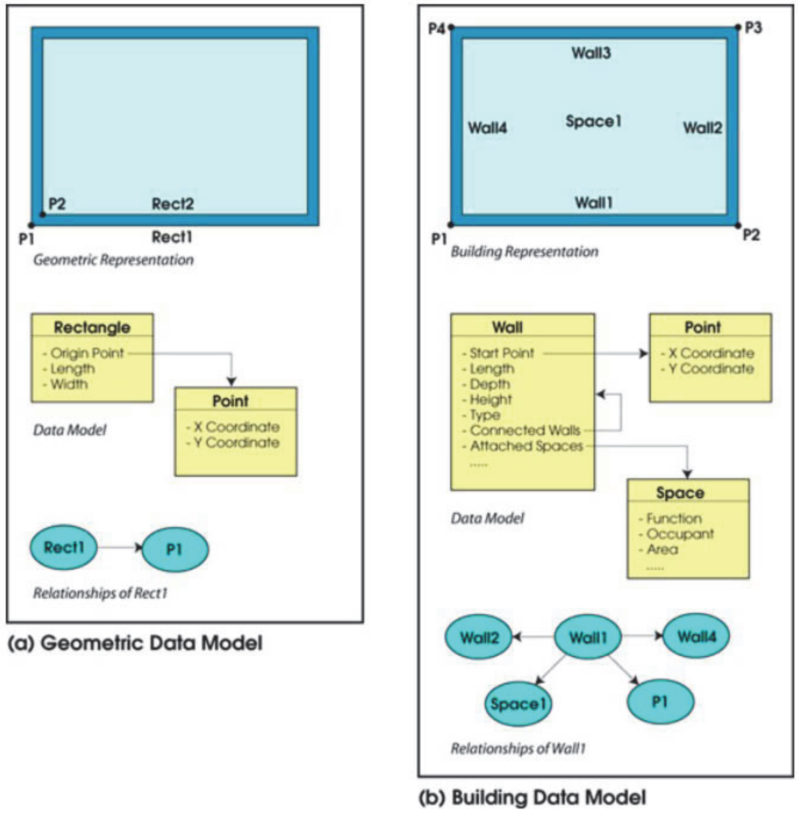


Figure 2-2 Geometric Model vs. Data Model (Khemlani, 2004)

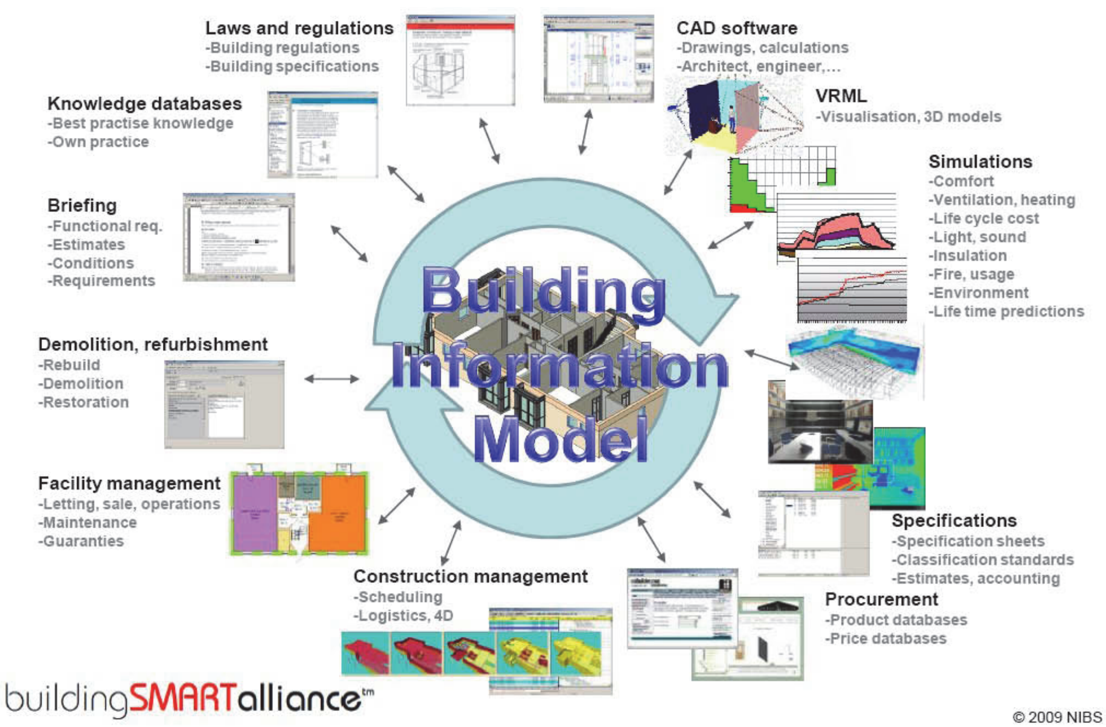


Figure 2-3 Lifecycle Information View (NIBS, 2011)

2.2.1 INDUSTRY FOUNDATION CLASSES (IFC)

Building owners are involved in a significant cost that arises from the lack of interoperability with regard to electronic facility information. buildingSMART®, formerly the International Alliance for Interoperability (IAI), has created a non-proprietary construction operations data model called Industry Foundation Classes (IFC). Their goal is providing "a universal basis for process improvement and information sharing in the construction and facilities management industry" (East, 2007).

IFC is a common data schema that provides all the proprietary software applications with a common framework to keep and exchange the facility information during all the phases of a facility's lifecycle (BuildingSMART, 2011). IFC leads to integration in the AECOO industry by defining a universal language to improve communication, productivity, delivery time, cost, and quality throughout the design, construction, operation and maintenance lifecycle of facilities (Mitchell and Schevers, 2005). IFC2x4 is the recent version and IFC is still under development to encompass more data related to facilities lifecycle (WBDG, 2011). STandard for the Exchange of Product model data (STEP) is another effort prior to IFC. STEP was initiated by the International Standard Organization (ISO) and focuses on the standard definitions for the representation and exchange of product information in general. SETP is used in various design disciplines such as mechanical design, ship design, etc. The experience gained in STEP is used to develop a more domain-specific model for the representation of building data by people involved in STEP (Khemlani, 2004). Figure 2-4 shows the IFC schema architecture. The IFC model consists of tangible building components such as walls, doors, beams, and abstract objects such as schedules, activities and so on (khemlani, 2004). The main layers of the IFC schema are (Buildingsmart-tech, 2011):

Domain layer: The entities defined in this layer cannot be referenced by the other layers. This layer contains final specialization of entities. In this layer, the defined entities are conceptually specific to an individual industry discipline.

Shared layer: The defined entities in this layer can be referenced by the entities in the domain layer. This layer has entity definitions for a beam, column, wall, flow controller, sound properties, etc. This layer has most of the common building entities.

Core layer: This layer is the most general layer within the IFC schema architecture. It comprises the basic structure, the fundamental relationships and the common concepts for all entities in the shared and domain layers. This layer contains entities that are abstract concepts to be used for the definition of entities in the higher levels. The defined entities in this layer can be referenced by all entities in the shared element layer and the domain specific layer.

Resource layer: The entities in this layer include basic properties such as geometry, material, quantity, measurement and so on, which are generic and not specific to a building. Entities defined in this layer can be referenced by all entities in the core layer, shared layer, and the domain specific layer. The entities in this layer cannot exist independently and should be referenced by other entities in the other layers.

The *IfcSharedFacilitiesElements* schema defines basic concepts in the facilities management domain. This schema, in addition to *IfcProcessExtension* and

IfcSharedMgmtElements, provide a set of models for applications intending to exchange data related to the FM domain (Buildingsmart-tech, 2011).

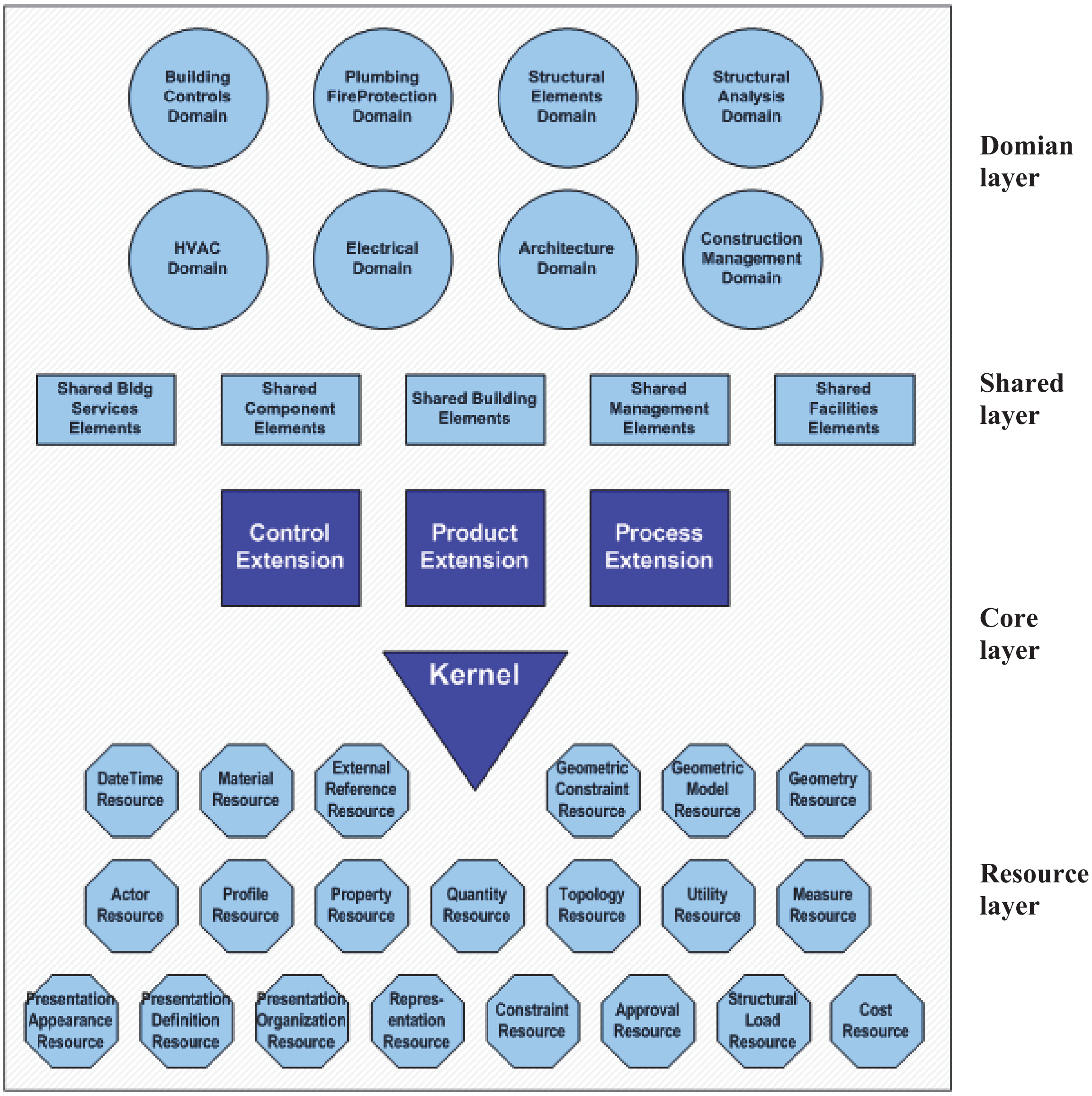


Figure 2-4 IFC Schema Architecture (Buildingsmart-tech, 2011)

During the lifecycle of a facility, different participants develop information and results that would be used by other participants later in the project. Information Delivery Manual (IDM) is a method used to define the exchange requirements between different processes, in which specific information provided in IFC by an upstream participant has to be transferred to a downstream party. IFC Model View Definition (MVD) determines the software requirement specifications to implement IFC interface to meet the exchange requirements defined by IDM. IDM is closely associated with MVD so that it can be said that IDM is a formal description of the various business processes, and MVD is how to implement this information in software by using IFC (BuildingSMART, 2011).

Some companies have developed geometry and properties viewers for IFC models. Most of these viewers such as Solibri Model Viewer (Solibri, 2012) and IfcViewer (KIT, 2012) are available to download for free. Some IFC viewers provide displaying selected objects attributes. It is also possible to turn on and off some entities through theses viewers. "IFC viewers are useful for debugging IFC translators, and to verify what data has been translated."(Eastman et al. 2011). IFC coordination view with the purpose of the sharing of building information models between the major disciplines of architectural, structural, and mechanical tasks during the design phase has been implemented and supported by most recent IFC compatible software. It contains definitions of spatial structure, building, and building service elements, required for the coordination of design data between these disciplines. There are some other IFC view definitions, such as IFC structural analysis view, and each of these views contains several exchange requirements (BuildingSMART, 2011).

2.2.2 CONSTRUCTION-OPERATIONS BUILDING INFORMATION EXCHANGE (COBIE)

Construction industry contracts require the contractors to handover some documents such as equipment list, product data sheets, warranties, and spare part lists to the owner for the

O&M phase. The tool used to collect the O&M data as a part of the BIM is called COBIE. It is a data standard for documenting the information needed to increase the efficiency of a facility's lifecycle and reduce its operating costs (WBDG, 2011). According to commissioning professionals, almost 30% of the content of document-based O&M manuals contains some kind of errors (East and Nisbet, 2010). COBIE collects O&M data as a part of BIM and the goal of COBIE is the improvement of the information capturing method during the design and construction phase in order to use for operations, maintenance, and asset management purposes (East, 2007). IFC-Model Based Operation and Maintenance of Buildings (IFC-mBomb) project showed an approach for data collection during the design and construction phase, and data handover for FM (IFC-mbomb, 2004). However, this project used ad-hoc methods before the development of COBIE.

COBIE has been created as a standard by the development team members of National Building Information Model Standard (NBIMS). Moreover, COBIE eliminates the creation and submission of boxes full of construction documents by the contractor to the facility operator at the completion of the construction phase. For example, Figure 2-5 shows the commissioning data of Genomics research center of Concordia University in the paper format where a separate room is specified to these data. As shown in this figure, in the traditional approach, a space should be allocated to keep the commissioning data. In order to complete COBIE, there are some processes occurring in different parts during the design phase that should be considered. These processes include architectural programming, design, construction quality assurance, supply chain management, and asset management. During each of these processes, some information relevant to COBIE can be captured (East, 2007).

Figure 2-5 Commissioning Data of Genomics Research Center

As mentioned previously, some of the information needed for the O&M phase is created during the architectural programming phase. The inventory of spaces and their functional requirements are examples of such information. During the design phase, information such as performance requirements of materials, products, and equipment, can be captured. The installed, tested, and commissioned equipment information is an example of information that can be captured during the construction phase (WBDG, 2011). COBIE helps to capture this information gradually. Its approach is to incrementally identify data exchange requirements that during the time, will build the entire COBIE specification. Between 2005 and 2009, COBIE has grown from an initial idea to an internationally recognized standard implemented in commercial software in the world (BuildingSMARTalliance, 2011).

As shown in Figure 2-6, designers provide information about spaces, systems, and equipment layouts. Contractors provide information about product data, as-built layout, tags, serial numbers, warranties, and spares parts of installed equipment (WBDG, 2011).

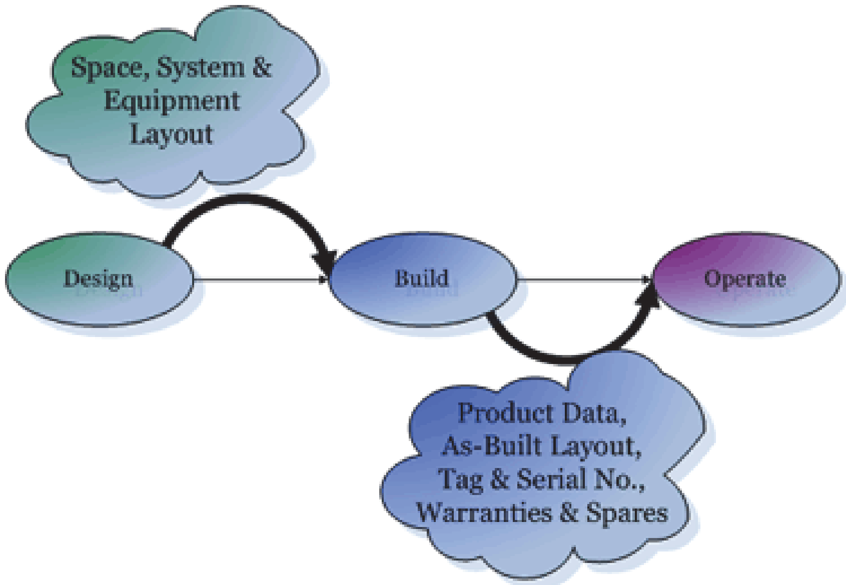


Figure 2-6 COBIE Process Overview (WBDG, 2011)

COBIE2 version was developed in 2010 including the worksheets and the data which should be entered in the field (WBDG, 2011). In order to simplify the usage of COBIE data by facility managers, Excel format (XLS) spreadsheet can be used. COBIE2 spreadsheet consists of sixteen mandatory worksheets which are *contact, facility, floor, space, zone, type, component, system, spare, resource, job, document, attribute, coordinate, connection*, and *issue* which are shown in Figure 2-7. All the worksheets are shown in detail in Appendix C (Figure C-1). *Pick-list* worksheet is an extra worksheet which is not mandatory and contains information usable for other worksheets. Some of the COBIE2 worksheets such as *facility, floor, space, zones*, and *systems* should be completed during the design phase. *Type* and *component* worksheets should be completed during both the design and construction phases as during each phase some data related to these two worksheets can be captured. *Job, resources*, and *spare* worksheets should be prepared during the construction phase and *contacts, documents, issues, coordinates, attributes*, and *connections* worksheets are common and can be prepared during any of the phases (WBDG, 2011).

Specific building systems are required for all projects to allow the spaces to perform as intended. For buildings, these systems include: electrical, heating, ventilating and air conditioning (HVAC), potable water, wastewater, fire protection, intrusion detection and alarms and other systems. Currently an optional COBIE set of data is the connections between equipment. Connections worksheet allows designers to specify how specific equipment are logically connected. For example, these logical connections helps a worker to know what other equipment would be effected if a valve closed. During the design some documents may be found useful for the future use. These documents can be linked by reference to the COBIE's documents data. The submittal register is a key aspect of COBIE since it is the approved submittals during construction that encompass the large amount of construction handover data sets. So this list can be specified by designers as requirement for documents in COBIE (WBDG, 2011).

2.3 FACILITIES MANAGEMENT (FM)

Facilities O&M include all the widespread services required to assure the built facility to perform the functions for which it was designed and constructed. O&M usually include the day-to-day activities required for the building and its systems and equipment to perform their intended operations. The O&M costs of a facility during its operation phase could be many times more than its initial construction cost (Becerik-Gerber, 2011). Almost 75% of the total cost of a facility is related to the O&M phase (Rundel, 2006).

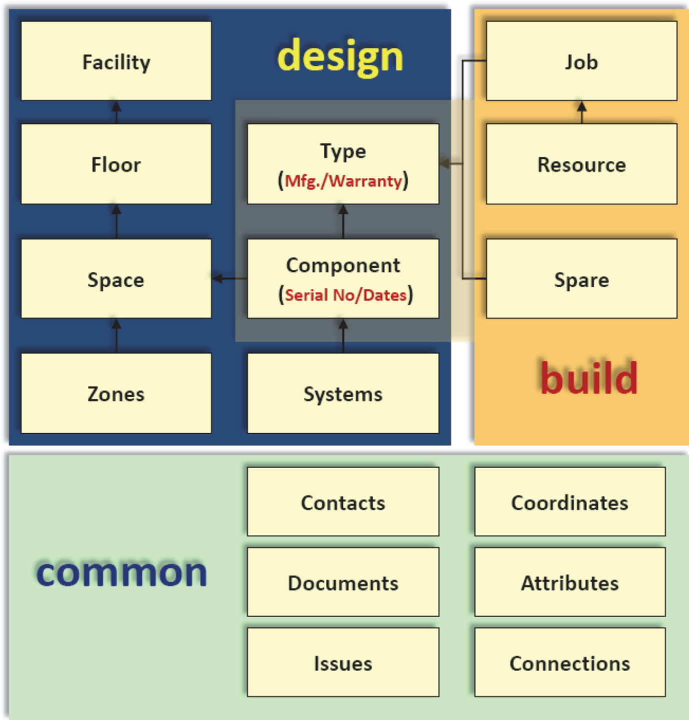


Figure 2-7 COBIE2 Sixteen Worksheets (WBDG, 2011)

Operations and maintenance are always coupled because a facility cannot be efficiently operated unless it is well maintained. The accuracy, relevancy, and timeliness of well-developed and user-friendly O&M manuals are important issues. So having a detailed, facility-specific O&M manual is required as a part of the commissioning process. The scope of O&M as mentioned includes some activities required to keep the performance of the facility satisfactory. Preventive maintenance consists of a series of time-based maintenance requirements that provide a basis for planning, scheduling, and executing scheduled (planned versus corrective) maintenance. Preventive maintenance includes adjusting, lubricating, cleaning, and replacing components (WBDG, 2011).

Computer Aided Facilities Management (CAFM) and Computerized Maintenance Management Systems (CMMSs) are useful tools for managing facilities during the O&M phase. The recreation of information usually should be done due to the loss of information during facility lifecycle phases. The access to a rich source of information alone does not guaranty the improvement. Information sharing and the improvement of process are important (Singh et al., 2009). The collaboration between the facility manager and planner can lead to decrease the FM cost. For example, providing the planner with the condition data collected by the facility manager during periods eliminates the cost of recollection and making decisions without such data (Singh et al., 2009).

Facility managers have the responsibility of keeping the function of the built environment by integrating people, place, process, and technology which can be done in more efficient way by using BIM technology (IFMA, 2011). Therefore, owners and facility managers can decrease the cost arising from the lack of interoperability by using high quality BIM during the most expensive O&M phase (Rundel, 2006). BIM of a facility can be used for asset management, space planning, and maintenance scheduling. The long term owner who knows the lifecycle cost concepts can understand the value of having an up-to-date data rich, query-able model of his or her building. BIM reduces the risk during the construction phase so the owners can decrease costs (Anderson, 2010).

Moreover, BIM provides the FM with the updated as-built plans which are useful for tenant's issues (Eastman et al., 2011). For example, when a tenant wants to build out a space, the facility executive typically has to ask the architect for a set of as-built drawings that may or may not be accurate, depending on the building's age and how many tenants have occupied the space (FacilitiesNet, 2008). In addition, the knowledge gained during the O&M phase can be transferred through the BIM model (Becerik-Gerber, 2011). Efficient transfer of requirements, design, and as-built construction data to the O&M phase is critical; however, this transfer has not been fully considered in the current practices (Mitchell and Schevers, 2005). BIM is still under development, and it can support FM practices with its functions such as visualization, analysis, and so on (Becerik-Gerber et al., 2011).

2.3.1 FM TOOLS

As mentioned before, the main goal of BIM is increasing the communication and collaboration between stakeholders through data interoperability during the whole phases of a facility's lifecycle. Although there are some open BIM formats claiming to meet BIM requirements, IFC can be considered as the most adopted interoperability format in the AECOO industry. From the interoperability point of view, FM tools which support the most updated IFC version can be considered as BIM-compatible tools. Some tools which meet some of the BIM definitions but do not support IFC are still considered as BIM-compatible tools by some studies (IBC, 2011).

The Institute for BIM in Canada (IBC) (2011) has recently published the *Environmental Scan of BIM Tools and Standards* which introduces BIM-compatible tools and their features, usable for planning & design, construction, and operations phases. In addition, Ahamed et al. (2010) has also introduced some commercial software used in FM sector.

However, some of this software do not support IFC format, but are categorized as BIM tools. Table 2-1 shows the tools usable in the operation phase. Some of these tools are identified and added to the table by the author (shown in bold).

2.4 BIM for FM

2.4.1 Current Status of BIM Implementation in FM

Becerik-Gerber et al. (2011) have done interviews with FM personnel to identify the role of BIM in FM. Their study shows that most of current FM functions are done manually and that using BIM in FM can decrease chances of errors and increase efficiency. They have also investigated the barriers in the implementation of BIM in FM. These barriers include: unclear and unmeasured benefits of BIM application in FM, lack of interoperability between BIM and CMMS, lack of demand for BIM by the owners at the commissioning phase, and lack of FM staffs' knowledge about BIM.

2.5 Integration and Visualization of FM Data

As mentioned in Section 2.2.1, IFC is an open BIM standard for data sharing and exchanging in AECOO industry. IFC Extensible Markup Language (ifcXML) is one of the most effective formats to transfer data to CMMS (NBIMS, 2007). However, the representation of operation, inspection and maintenance information in IFC is still under development. Hassanain et al. (2000) have proposed an IFC-based data model for integrated maintenance management. The proposed approach includes entities, such as IfcCondition, IfcInspection, IfcRresource, and IfcCostElement for supporting FM integrated systems.

Table 2-1 BIM Tools Usable for Operation Phase in AECOO Industry

Product name	Vendor name	Main features	IFC suppo-rt	Use in AECOO industry		
				Planning & design	Const-ruction	Opera-tions
Allplan Facilities Management	Nemetschek	FM	*			*
Archibus	Archibus, Inc.	FM				*
ArchiFM	Vintocon/GRAPH ISOFT	Object-oriented approach, BIM-based facility maintenance modeling	*			*
ArTra BIM	CADPIPE	Interface to link 3D CAD			*	*
Dexter +Chaney	Spectrum Construction Software	Project management, construction accounting, equipment management and data sharing.				*
Field BIM (Vela Suite)	VELA Systems	Field BIM for construction	*	*	*	*
FM:Interact	FM:Systems, Inc.	FM				*
Glue	Horizontal systems	Web-based BIM management				*
Maximo	IBM	Asset management	*			*
Microsoft Dynamics	Microsoft Corporation	Construction project management				*
Project Document Manager	Joint partnership with McGraw Hill Construction	Create, publish, manage and distribute project information				*
Rambyg		Web-based	*			*
Ryhti	Olof Granlund	Maintenance, planning and monitoring, request management and monitoring	*			*
Tririga	IBM	Space management, facility maintenance, and energy management	*			*
Vizelia	AXA	Space management, asset management	*			*

The IfcFacilitiesMgmtDomain schema provides a set of models that can be used to exchange information for managing the movement of people and equipment, capturing information concerning the condition of components and assets, capturing requests for action to be carried out and so on. In order to increase the efficiency of FM, the integration of COBIE data in BIM and FM software would be beneficial. There is a possibility to add COBIE data to BIM-based tools such as Revit (Autodesk, 2011). In addition, CMMS database can be populated by COBIE data directly (Maximo, 2011).

Kyle et al. (2002) developed a decision support tool for asset managers to predict the service life in asset management plans in 2D. According to Kyle et al. (2002), the visualization of natively non-visual data for large asset inventories can be a highly useful cognitive aid for grasping the overwhelming amount of information required for decision making in asset management. The availability of a standard data and information flow in the domain of "Service Life Asset Management" is identified as a major requirement.

Hallberg and Tarandi (2011) used a BIM tool as a repository and media to present lifecycle information of the exterior part of a hospital building. In their case study, attributes such as "Date of inspection" and "Condition class" were added as additional object attributes and visualized in a 3D model. They have also used degradation models to visualize performance-over-time of windows and the concrete structure in the 4D model by the use of a color scale. The first degradation model is the performance-over-time of windows in terms of condition classes, classified in five conditions from "as new" to "extremely bad". Each condition is represented by a color that changes with the passage of time. The second degradation model is a carbonation model and shows the dynamic relation between the depth of carbonated concrete and the depth of the protecting concrete cover by the pass of time. They argued that visualization and simulation of degradation in 4D will give a more understandable overview of the lifecycle performance and maintenance, repair and rehabilitation (MR&R) needs of buildings than if presented in tables and graphs.

Work orders are usually used as the main source of information related to component maintenance. Work order information is usually stored in paper format or in CMMS and not considered with other facility information such as space, component, system, etc. (Akcamete et al. 2011). Akcamete et al. (2011) have stored and visualized work orders information in a 3D digital facility information database to do spatio-temporal analysis. For this purpose, the trend of maintenance and repair tasks for proactive maintenance decisions is obtained and the work orders are linked with BIM for spatio-temporal analysis. The comparison of the amount of work orders associated with spaces and components are visualized. They have used the weekly number of hot/cold calls and thermostat re-calibration work orders for a specific space. They resulted through the line chart that the thermostat re-calibration work orders may be the cause of hot/cold calls as both of them had almost the same number of work orders during a specific time. Visualizing the amount of work orders alone can be useful to see which components or spaces have abnormal amount of work orders. Work orders history of a room or a component for a relatively long period is used to visualize the trends by using static line charts.

Kaetzel and Clifton (1995) identified visual information as an increasingly important aid in the display of knowledge that will improve the usefulness of expert systems. Although 4D visualization is mainly used in construction scheduling, progress management and workspace planning (e.g., Hammad and Motamedi, 2007; Staub-French and Khanzode, 2007; Dawood and Mallasi, 2006), it can also help to get a better overview of Service Life Performance Analysis (SLPA) results, as the performance-over-time of buildings is characterized by spatio-temporal and logical oriented behavior (Hallberg and Tarandi 2011). Rad and Khosrowshahi (1997) and Khosrowshahi and Banissi (2001), demonstrated 4D visualization of some components for building maintenance where the life expectancy of components is mathematically calculated. In their research, a 4D visual model is used as a tool for lifecycle performance evaluation to assist in the development of long-term maintenance plans.

Linnert et al. (2000) used 4D visualization to demonstrate the behavior of a single-family house during its lifecycle and they used two methods for visualization. In the first method, when a building component service life is reached, it becomes transparent (Figure 2-8). In the second method, the building component changes color as it becomes older based on a color scale (Figure 2-9).

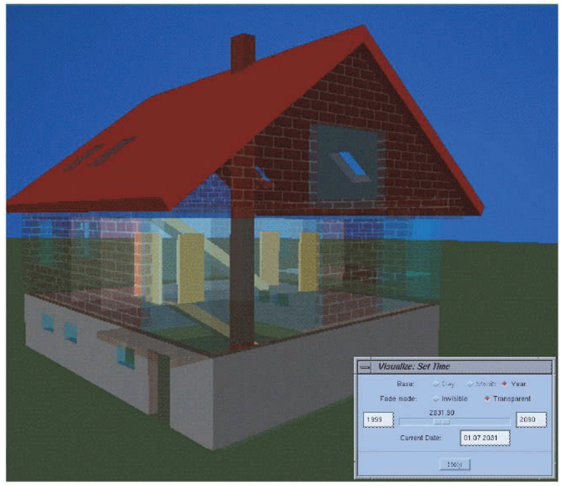


Figure 2-8 Transparency Method for the Objects that Have Reached the End of Their Life Expectancy (Linnert et al., 2000)

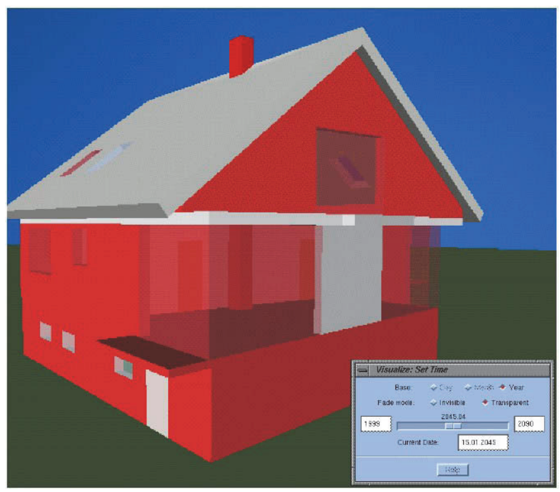
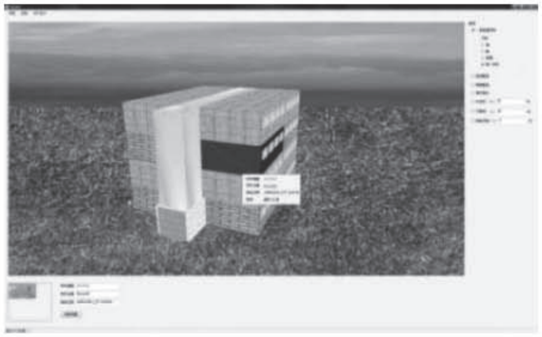


Figure 2-9 Objects with Different Colors According to their Ages (Linnert et al., 2000)

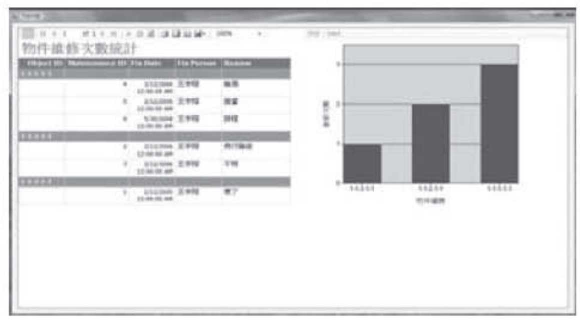
Bjørkhaug et al. (2005) presented a web-based and IFC-compatible application for lifecycle analysis based on dose-response functions. However, lifecycle analyses results were not visualized in 3D models. Chen and Wang (2009) proposed a 3D visualized approach for maintenance and management of facilities that uses an external database and OpenGL technology to build a virtual facility where the administrators can select components and obtain the maintenance or management information (Figure 2-10).



(a) 3D visual interface

(b) Design and maintenance history of digitized storage facility

(c) Integrated MM and data collection and storage



(d) MM information processing and analysis

Figure 2-10 Conceptual Illustration of the Facility Maintenance and Management approach (Chen and Wang, 2009)

2.5.1 VISUAL ANALYTICS FOR CAPTURING CAUSE-EFFECT RELATIONSHIPS

Analyzing causes-effect patterns can be done using field studies, statistical analysis and data-mining methods. The spatial distribution of identified problems is an important factor that is not easy to capture without having a detailed model of the facility that can be used to visualize the location and distribution of detected problems in 3D or 4D. El-Ammari et al. (2006) have investigated the integration and visualization issues in large-scale location-based FM systems. However, they did not consider the potential deterioration cause-effect relationships. Wang et al. (2010) have developed an interactive visual analytics system for bridge management. However, in order to apply this type of visual analysis, it is necessary to integrate the data of CMMS with a 3D model of the facility. For example, Akcamete et al. (2010) have demonstrated the benefits of using the 3D visualization capabilities of BIM to identify maintenance trends. However, in that study, the data have been manually added to the BIM because of the lack of interoperability of the CMMS and the BIM software.

Ahluwalia (2008) and Hegazy et al. (2010) have developed indicators of the condition of five building components (roof, window, boiler, secondary switchgear and fire alarm system) using reactive maintenance data. They have also identified some interrelationships among various building components. For example, if horizontal and vertical cracks on a load-bearing wall are found, the reason could be water infiltration in the cavity wall. Table 2-2 shows the interrelationships among various building components (Ahluwalia, 2008).

Defining the relationships between components and spaces in BIM is the most important and useful issue related to the topology of a building. Some of these relationships are already defined in IFC and have been standardized. There are two ways of connectivity between components in IFC which are physical and logical. In logical connectivity, there is no physical connection between two components. Logical connectivity can be interpreted as non-physical connection. E.g. the connection between a light switch and a light fixture can be considered as logical connectivity as the cable which connects the switch with a light will not be instantiated in the model so there will not be a physical connection. It is not possible in logical connectivity to explain and model a cable in detail (Liebich, 2009). In logical connectivity, components are connected via *ports*, but in physical connectivity components are connected via a realizing element such as *IfcFlowFitting*.

Table 2-2 Interrelationship among Various Building Components (Ahluwalia, 2008)

Observation	**Cause**	**Check**	**Result**	**Strategy**
Low room heating/cooling	Window/door not closing properly (functional problem)	Check for hardware problems	More load on mechanical system	Repair window/door problem
Horizontal and vertical cracks on load-bearing wall	Water Infiltration in cavity wall	Check for roof flashing (cracks on above level), or foundation problems	If cracks on upper level, infer repair flashing; else repair foundation	Repair foundation or roof flashing
Damaged ceiling in washroom	Plumbing fixtures leakage at upper level	Check washrooms on upper floor	Mould formation (health and safety concern)	Repair plumbing leakage on top floor
Damaged/old breaching or boiler	Breaching or boiler repair/ replacement	Check boiler condition (replacement/repair) and review breaching condition accordingly	Inoperable boiler or highly deteriorated breaching	Boiler and breaching go together
Sudden outburst of water from water fountain on main floor	Clogging/blockage in pipes	Check for hydrostatic pressure in the sewage pipe	Ceiling damaged	Clear and depressurize pressure in sewage pipe

In IFC, *IfcRelConnectsElements* is used for physical connectivity and *IfcRelConnectsPorts* is used for logical connectivity between building components. Figure 2-11 shows an example of connectivity between two building service elements "*Tee*" and "*Duct*" (Liebich, 2011). In this figure, *IfcRelConnectsPorts* is used to connect the *Tee* to the *Duct* where only compatible elements are allowed to connect to each other. If the optional attribute RealizingElement of *IfcRelConnectsPorts* which is the

"*Connector*" in this figure is used, the connectivity is changed from a logical connectivity to a physical one (Becker et al., 2011).

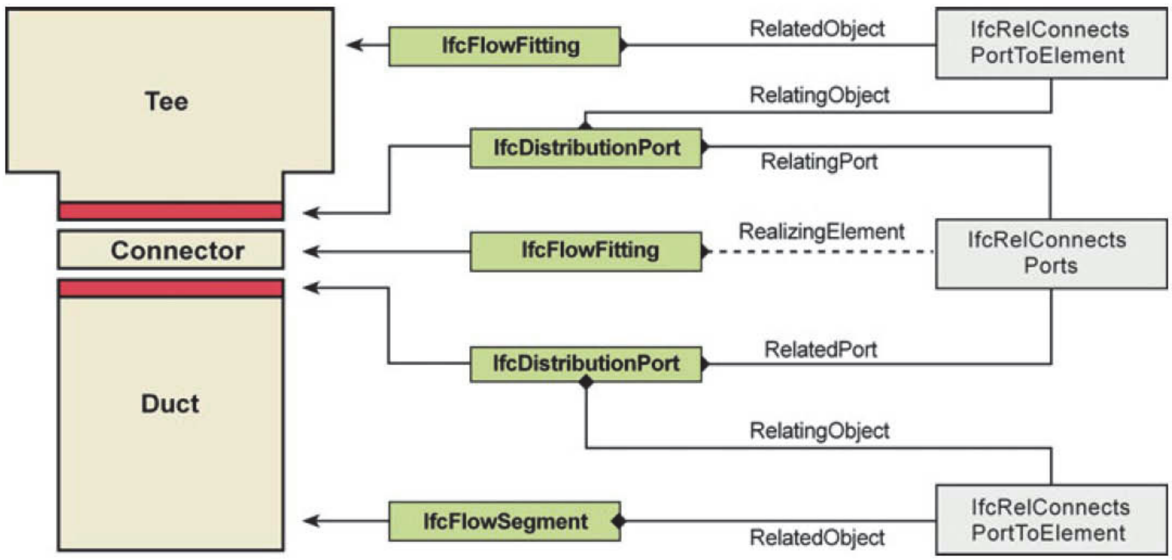


Figure 2-11 Connectivity Example Between Two Building Service Elements (Liebich, 2009)

2.5.2 IBM Intelligent Building Management Solution

The IBM Intelligent Building Management solution was built and designed around the elements of visualization, intelligence, interconnected, instrumented and physical as illustrated in Figure 2-11 (IBM, 2012). Each layer identified in this figure provides an important aspect of the solution: (1) The physical layer contains the actual equipment and physical elements that need to be monitored. (2) The instrumented layer contains the building management system (BMS), which collects all of the real-time meter and sensor data. It aggregates this data into meaningful and actionable information. The BMS is configured to raise alarms based on client-defined thresholds. (3) The interconnected layer contains two domain areas. One domain area uses open standards to collect the necessary metrics and alarms from the various BMS installed across the enterprise. The other domain aggregates BMS data into a single normalized format. With this aggregation, access is available to information that was unavailable previously from an enterprise perspective. (4) The intelligence layer provides the analytics, maintenance, and operational activities. This information enables the understanding of the optimum operating parameters for energy assets. It also enables management to act immediately in response to events, such as operational malfunctions. It provides ongoing visibility to energy efficiency over time, reducing energy waste. Maintenance and operational activities are enhanced with more information coming from BMS analytics and real-time alerts. This information enables technicians to identify the problem quickly, so that they can resolve it sooner. (5) The visualization layer makes valuable cross-system information viewable on a single dashboard. Combining previously unrelated data and business logic from two or more sources can create new insights. The dashboard is role-based, with access control. By using the dashboard, the operator can launch other applications that are appropriate to the context of the work that the operator is currently performing.

Although the IBM solution has powerful tools for analytics and visualization, it does not provide visual analytics functionalities.

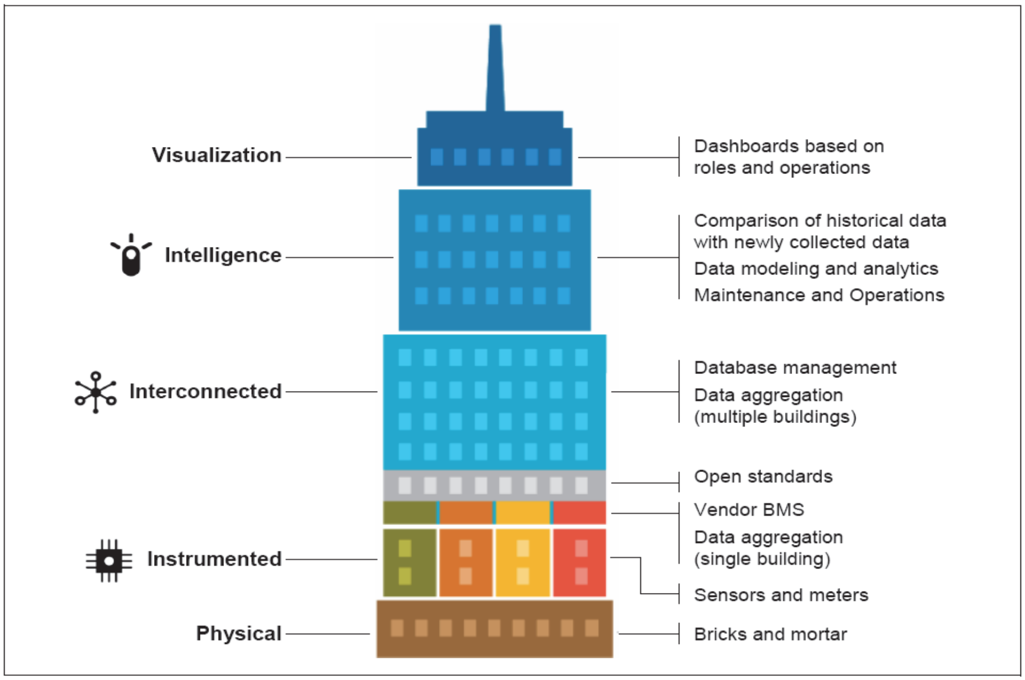


Figure 2-12 Architectural Elements of the Solution (IBM, 2012)

2.6 Augmented Reality (AR) and Data Fusion in Construction

Augmented Reality (AR) integrates a real-time view of the user's environment and virtual objects within the same environment. Either the real view or the virtual view can be used as a background while the other type of objects can be superimposed and form a composite view. AR can extend the perception capabilities of the user in the real world and his or her interaction with its objects, providing information that the user cannot detect personally and directly (Izkara et al., 2007). AR has been used in construction for supporting bridge inspection (Hammad et al. 2002), for visualizing construction equipment operations (e.g., Behzadan et al., 2008), for supporting the interaction of two users operating two virtual cranes and communicating with each other (Hammad et al., 2009), and for automatic construction progress monitoring (Golparvar-Fard et al., 2009).

Data fusion was initially defined by the U.S. Joint Directors of Laboratories (JDL). Data fusion involves combining information in the broadest sense to estimate or predict the state of some aspect of the universe (Steinberg and Bowman, 2001). Shahandashti et al. (2011) have reviewed some examples of recent applications of data fusion in civil engineering and have presented some of the potential benefits, such as enhancing confidence, improving system reliability, reducing ambiguity, improving detection, extending spatial and temporal coverage in sensing systems, and increasing dimensionality. However, the possibilities of using AR and data fusion in O&M have not been explored yet.

2.6.1 Location Tracking Using Ultra Wideband (UWB) Technology

Several tracking methods can be used for tracking the location of objects in AR applications such as GPS and Real Time Location System (RTLS). UWB is a RTLS wireless technology for transmitting large amounts of digital data over a wide spectrum of frequency bands at very low power (less than 0.5 milliwatts) (Ghavami et al., 2004). Researchers have started to investigate the usability of UWB on construction sites. For example, Teizer et al. (2007) have investigated the usability of a UWB tag attached to a crane hook to track the position of the hook. Giretti et al. (2009) have indicated that UWB behavior is rather constant during most parts of the construction progress. They have noted that, in an open area, tests confirm an accuracy of about 30 cm. Cho et al. (2010) have discussed error modeling for an untethered UWB system for indoor construction asset tracking. Zhang et al. (2010) and Rodriguez et al. (2010) have discussed the feasibility of tracking construction resources for better productivity and safety on site. UWB is used as the location tracking method for AR in this research.

2.7 DATABASES

A database is composed of tables to store data and a relational database contains tables that are related together. CMMSs such as FM:Interact use a relational database to store and present FM data (FM:Systems, 2011). In addition, BIM is supported by a database to store and retrieve required data. For this matter, databases are used in this research.

For the creation of relationships, a field from one table should be used as a field in a related table. A *primary key* is a field, or a combination of fields, with a value that makes each record or each row in a table unique. Each table in a database has a primary key which is included as a new field in another table to create a relationship with that table. The new created field in the second table which is a shared primary key of another table is called a *foreign key***.** There are three different kinds of relationships between tables. *One-to-one* is used when a single record in one table is related to a single record in another table, and vice versa. *One-to-many* is used when one record in a table is related to many records in another table. For example, one supplier can provide many assets, so the *Suppliers* table resides on the "one" side of the relationship, while the *Assets* table sits on the "many" side (Figure 2-13). *Many-to-many* relationship can be used for relating several records in one table to several records in another table (Microsoft, 2012).

Structured Query Language (SQL) is a standard language for accessing and manipulating databases. Data can be retrieved from a database through queries (Wikipedia, 2012).

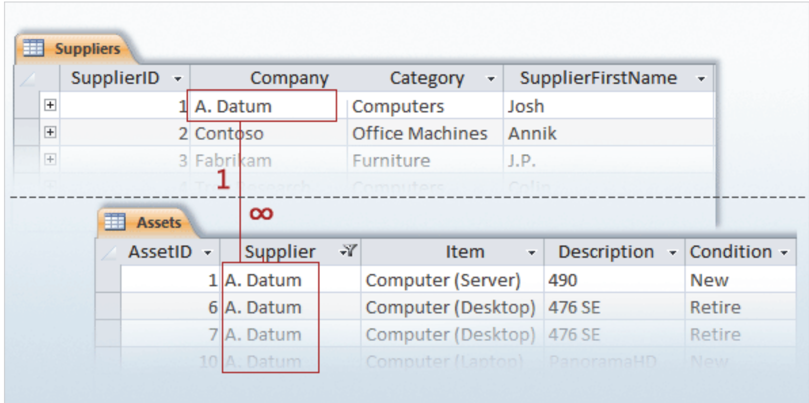


Figure 2-13 One-to-Many Relationship Example (Microsoft, 2012)

2.8 SUMMARY

In this chapter BIM technology, data exchange standardization, FM and the benefits of BIM applications for FM were reviewed. Moreover, AR technology and its usage in AECOO is explained. The literature showed that BIM technology can increase the productivity and efficiency in AECOO industry. This chapter showed the importance of using standardized open BIM for FM in terms of visualization during the O&M phase which is the most costly phase of facility's lifecycle. Our proposed approach is based on the reviewed literature related to technologies and standards in AECOO industry.

CHAPTER 3 VISUAL ANALYTICS IN FM

3.1 INTRODUCTION

As explained in Section 2.3, O&M is the most costly phase of facility's lifecycle. The completeness and correctness of FM required data have a significant impact on the O&M quality. BIM can improve the quality of FM as BIM covers the whole lifecycle of a facility from the design phase until the demolishing phase. At the same time, COBIE as a standardized specification can be used for data exchange between contractors and owners. Visualization is one of BIM's benefits which can help to improve the quality of FM.

In this research, based on related literature review in Subsection 2.5.1 and on interviews with the personnel of the FM department of Concordia University, several potential deterioration/failure cause-effect relationships were identified based on inspection and condition assessment results and maintenance history data of facilities' components. An example of visual analytics in the context of FM is the visualization of all possible causes of heat problems in a room. Visualizing the relationship between cracked/repainted walls and possible causes, such as plumbing problems, based on inspection and maintenance history data is another example. In order to realize visual analytics for FM, a database structure and several queries were defined by combining several assets' attributes based on the identified cause-effect relationships. These queries provide the opportunity for facilities managers and technicians to visualize and analyze a large amount of data. Furthermore, we investigated visualization methods to improve the efficiency of the visual analytics.

Figure 3-1 (a) shows the current practice of using CMMS. A technician inputs data, such as inspection and maintenance information, into the CMMS database. At the same time, he/she can retrieve the information related to work orders. Facilities managers are provided with reports regarding maintenance issues. Figure 3-1 (b) demonstrates the proposed approach using BIM-compatible tools to visualize FM data. CMMS can complement all needed data for a comprehensive BIM database. In this approach, CMMS and the visual analytics engine use a BIM database to store data, so both facilities managers and technicians can have FM data visualization by making queries.

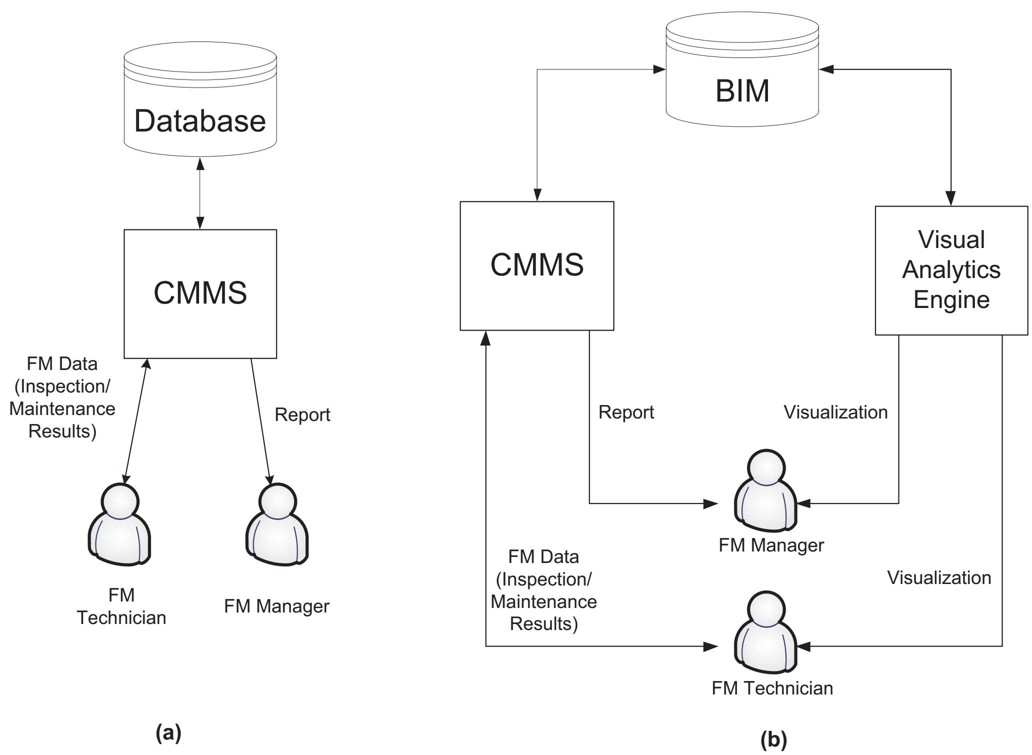


Figure 3-1 (a) Current Practice of Using CMMS, (b) Using BIM-Compatible Tools to Visualize FM Data

3.2 PROPOSED METHOD FOR VISUAL ANALYTICS IN FM

Figure 3-2 conceptually shows the steps of the integration and visualization of FM data. These steps include: (1) Standardized data integration and new attributes definition, (2) Logical and spatial relationships definition, (3) Cause-effect relationships and queries definition, and (4) Visualization. These steps are explained in detail in the following Subsections.

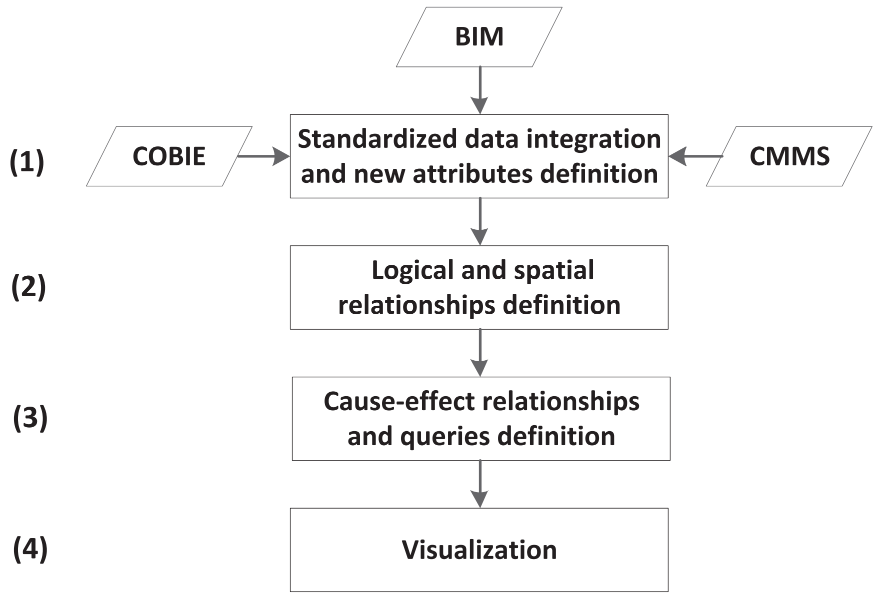


Figure 3-2 Conceptual CMMS-BIM Integration for Cause-Effect Visualization

3.2.1 Standardized Data Integration and New Attributes Definition (Step 1)

As mentioned in Subsection 2.2.1, IFC is a widely accepted standard format between BIM-based tools and CMMSs for data sharing and exchange. However, most of the BIM-compatible tools which support IFC do not completely comply with IFC2x4. Moreover, as mentioned in Subsection 2.2.2, COBIE provides facilities managers with the O&M required data. COBIE2 is the latest version and contains various data related to the O&M of buildings. However, some data are still required to be added to COBIE2 such as inspection frequency data. As BIM has not been fully developed yet, COBIE is considered in our research as a separate data source. Eventually, BIM will encompass all the information related to a facility and COBIE data will be a part of BIM. The lack of standardization makes it difficult for BIM tools and CMMSs to interoperate with each other. The first step in our approach is to integrate data from COBIE, BIM and CMMS (Figure 3-2). Figure 3-3 conceptually shows the overlapping of data in the current status of practice (a) and in the future (b). In the current status of practice (a), some attributes such as *cost* are already defined and common between IFC, CMMS, and BIM tools. There are some other attributes which are defined in IFC, and some CMMS and BIM tools. In the future, it is expected that IFC as the standardized format for interoperability will include all the attributes defined in CMMS and BIM tools.

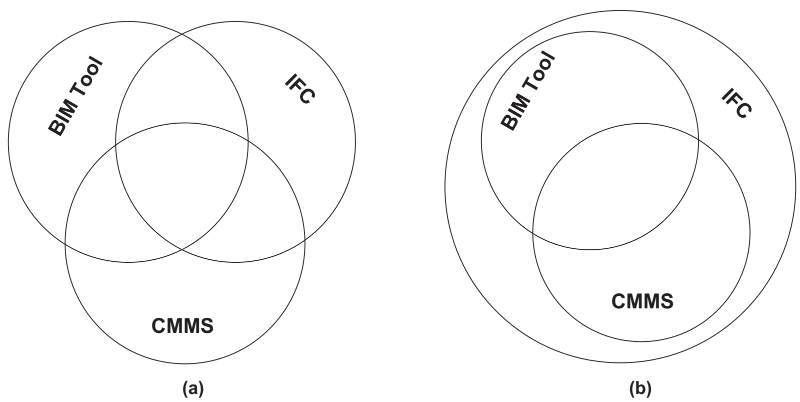


Figure 3-3 Current Status (a) and Expected Future (b) of Attributes in IFC, CMMS, and BIM Tools

Integration of commissioning data with BIM

Figure 3-4 shows the different scenarios of the integration of facilities lifecycle data. In this figure, (a) shows the current status of practice for the integration of commissioning data with the CMMS. In this method, the commissioning data is manually entered in a CMMS. This method is not efficient and is prone to errors. (b) and (c) show the short term proposed plans for the O&M data integration where in (b), the COBIE file is prepared using commissioning data and then is exported to the CMMS database using an

API, and in (c), commissioning data is added to the 3D BIM in the BIM tool and then is used to populate the database of the CMMS using an API. (d) shows the future vision, where the BIM database will encompass all the lifecycle data. In this case, the CMMS and the BIM tool can interact with the BIM database for different purposes such as visualization.

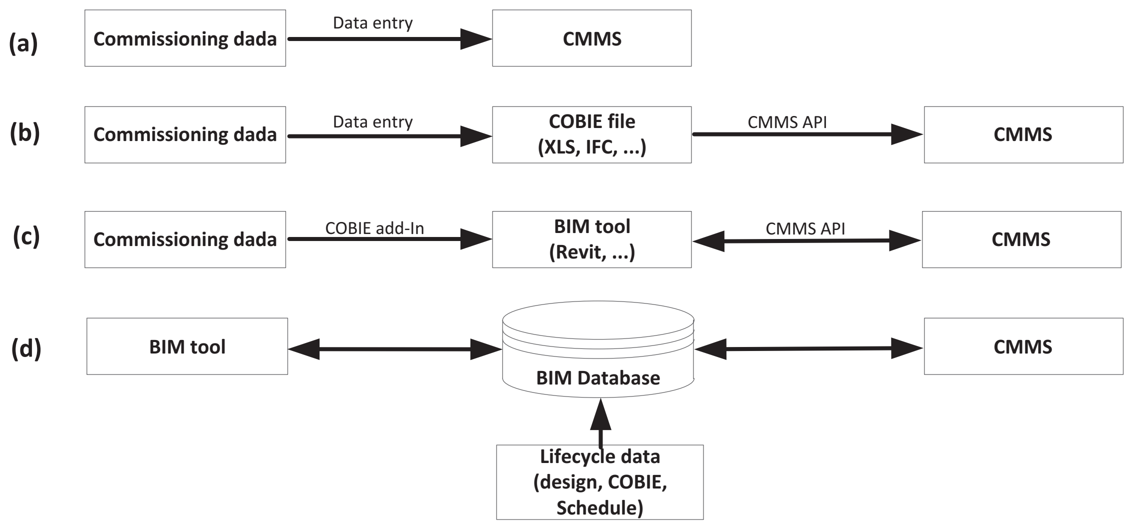


Figure 3-4 Conceptual COBIE-CMMS Integration Methods

Integration of O&M data with BIM

As explained in Subsection 2.5, Hallberg and Tarandi (2011) have studied the 4D visualization technology usage in the performance-over-time behavior of components. They have used a BIM-based design tool as the repository of the inspection data of a facility. As explained in Subsection 2.3.1, most of the available CMMSs are not compatible with BIM and they do not fully support IFC. On the other side, 3D models are not used as the repository of O&M data by facilities managers. Synchronizing BIM-compatible tools with CMMSs is a practical way for visualizing O&M data, as the inspectors do not have to deal with the 3D model.

It is also proposed to link the components to their corresponding pictures and documents in the BIM tools. This linkage is defined by the relationship *IfcRelAssociatesDocument* in IFC. This linkage helps the inspectors and maintenance technicians to find the desired components in a shorter time. In addition, maintenance technicians can get the related electronic manuals and maintenance instructions in a high quality format immediately, by clicking on the component. This will decrease human errors and time related to finding the documents. Figure 3-5 shows the BIM model of the mechanical room of the Genomics research center of Concordia University as an example with some related pictures and documents such as the guaranty of the chiller.

Definition of new attributes

As mentioned above, BIM ideally will include all the information related to components' lifecycle. At present, some of the components' attributes that are not available yet in BIM tools and CMMSs should be added. Examples of these attributes include condition history of a component, based on inspection and the number of work orders. Some of these new defined attributes will be filled by technicians in CMMS and synchronized with the BIM tool for visualizing the queries. Components' inspection history can also be used for discovering cause-effect patterns or deterioration trends in order to update the preventive maintenance schedule.

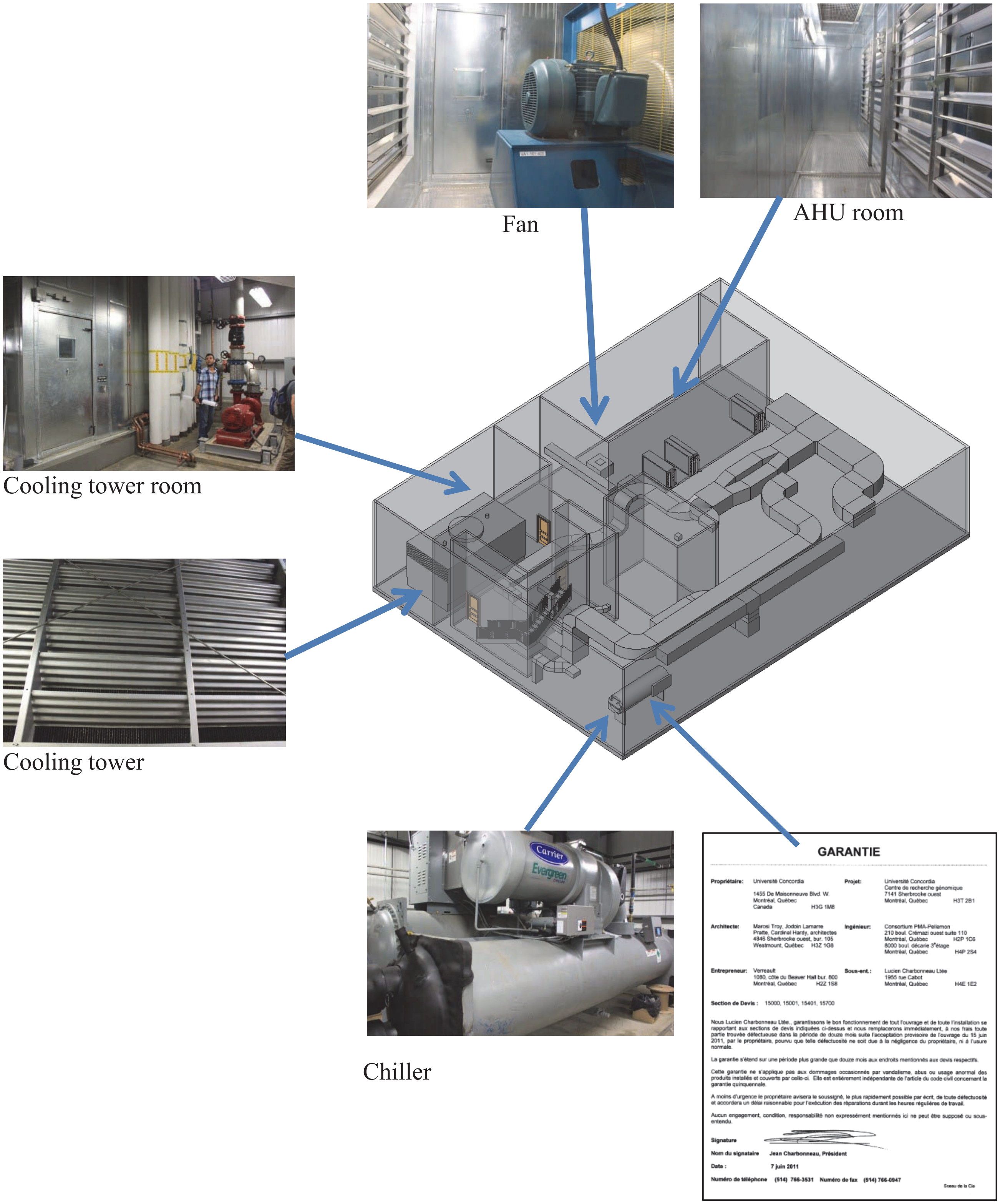


Figure 3-5 BIM Model of the Mechanical Room of Genomics Research Center of Concordia University with Related Pictures and Documents

3.2.2 Logical and Spatial Relationships Definition (step 2)

We use three types of relationships between components and spaces: (1) Logical relationships: Objects can be physically connected or logically related in the IFC. The logically related components are not necessarily physically connected. For example, the connection between a light switch and a light fixture, as the cable connecting the switch to the light is not usually instantiated in the model, can be considered as a logical relationship (Liebich, 2009). *IfcRelConnectsElements* is defined in IFC providing the generalization of the connection between elements which is a one to one relationship; (2) Spatial relationships: A spatial relationship defines the relationship between components and/or spaces which are physically related (e.g., containment and adjacency); and (3) Time-dependent relationships: Components and spaces' conditions can be presented at different times using temporal analysis. In the following discussion, we will use $C_{p,t}^{i}$ to represent component *i* having property *p* at time *t*. Similarly, $S_{p,t}^{j}$ represents space *j* having property *p* at time *t.*

Various types of logical and spatial relationships should be defined. The categorization of relationships is done based on the literature and interviews with FM personnel. Then, a method is investigated for representing these relationships using IFC concept and tools.

We define relationships between related entities (E^i and E^j) using the following notation: $R_{m,n}^{E^i,E^j}$ where *m* defines the type of relationship (i.e. logical (*l*) or spatial (*s*)) and *n* defines the category of relationship (e.g., same HVAC system, same department). Based on this definition, the following are different possible groups of relationships: (1) Relationships between components ($R_{m,n}^{C^i,C^j}$); (2) Relationships between spaces ($R_{m,n}^{S^i,S^j}$); and (3)

Relationships between spaces and components ($R_{m,n}^{S^i,C^j}$). In Figure 3-6, $R_l^{S^a,S^b}$ shows a logical relationship between S^a and S^b that are not adjacent or physically connected but logically related. For example, S^a can be a mechanical room and S^b can be a space which is located at a different floor from S^a but S^a provides S^b with heating/cooling. This kind of relationship is defined in IFC through *IfcRelServicesBuildings* which defines the relationship between different zones and spaces or spatial zones. In some facilities there are more than one mechanical room and each of them supports some of the facilities' spaces which means the existence of several service systems in a building. *IfcRelServicesBuildings* also defines relationships between a heating system, as an example of a building service system, and the sites, building, stories, spaces, and spatial zones.

$R_l^{C^1,C^4}$ shows the logical relationship between C^1 and C^4 which are logically related but not physically connected. For example, the relationship between a boiler located in the mechanical room S^a and a supply diffuser in S^c. $R_s^{C^2,C^3}$ shows the spatial relationship between C^2 and C^3 that are located in S^b and physically connected (e.g. ducts and supply diffusers). $R_s^{S^b,S^c}$ shows the spatial relationship between two spaces S^b and S^c that are adjacent. In addition, C^1 has a logical relationship with S^c ($R_l^{C^1,S^c}$), but spatial relationship with S^a($R_s^{C^1,S^a}$). The spatial relationship between a component and a space is defined in IFC by *IfcRelContainedInSpatialStructure*, which is defined to assign elements to spaces where they are preliminary contained. As any element can only be assigned once to a certain spatial structure, the desired element should be assigned first to a specific space through *IfcRelContainedInSpatialStructure* and then referenced by the other space which it spans, using *IfcRelReferencedInSpatialStructure.* For example, a lift shaft may be contained by the ground floor, but referenced by all floors, through which it extents.

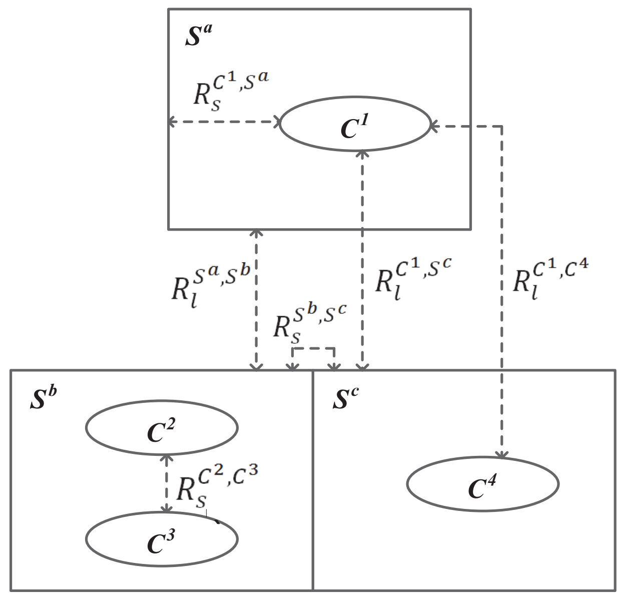


Figure 3-6 Examples of Spatial and Logical Relationships between Components and Spaces

3.2.3 CAUSE-EFFECT RELATIONSHIPS AND QUERIES DEFINITION (STEP 3)

The interrelationships among various building components make it difficult to understand the cause-effect relationships in facilities (Ahluwalia, 2008). According to Ahluwalia (2008), a deficiency in one component can affect one or many other components. A window/door which has insulation problem, can affect the room temperature. This cause has not been considered by Akcamete et al. (2011) in their visual analytics of rooms heating/cooling problem. In fact, there are different possible causes leading to a certain effect. In order to have a more reliable visual analytics, all these causes should be considered. In this method, cause-effect relationships are defined based on the relationships among components and spaces. Table 3-1 shows some of the possible causes of low heating/cooling problems in a specific space. Cases (1) and (2) are considered in other studies as the possible causes. A boiler malfunctioning, a local heating system problems, and the existence of other equipment in the space generating heat, are examples of other possible causes which should be considered. For example, as the boiler is connected to the heating system, problems related to the boiler can be the cause of a heating/cooling problem in the space. Ducts deficiency and supply diffuser problem can be considered as such causes as well.

Table 3-1 Possible Causes of Heating/Cooling problem in a Space

1	Window/door not closed properly (functional problem) (Ahluwalia, 2008)
2	Temperature sensor of thermostat malfunctioning (Akcamete et al. 2011)
3	HVAC malfunctioning (Boiler malfunctioning, ducts and supply diffuser deficiency)
4	Heat exchange between adjacent spaces
5	Other equipment in the space generating heat
6	Window/door isolation problem

As mentioned above, the detection of the main causes of the high temperature problem related to a space is realized through the visualization of all the possible causes in terms of their number of work orders. For example, components with less than three, equal to or more than three, and zero number of work orders are assumed to be in fair, bad, and good conditions, respectively.

In addition, some queries are built based on the newly defined attributes in a relational database using SQL. For example, components' inspection history can be used for discovering cause-effect patterns or deterioration trend in order to update the preventive maintenance schedule. The results of the queries help in the visual analytics of the cause-effect relationships between components and spaces. Figure 3-7 shows the relational database developed in Microsoft Access (Microsoft, 2012). Queries are defined based on the tables including: ELEMENT, SPACE, WO, DIST_SYS, and DIST_SYS_TYPE where the tables are related through *primary keys* (Figure 3-7). Thses tables are explained in the following:

(1) *DIST_SYS_TYPE* (Distribution system type) table: This table includes all the distribution system types used in the building. HVAC, plumbing, electrical, and sewage are the systems defined in this table where each system is identified by DIST_SYS_TYPE_ID.

(2) *DIST_SYS* (Distribution system) table: This table includes all the distribution systems of a building. Each distribution system has an ID (DIST_SYS_ID) and is valued through a distribution system type (DIST_SYS_TYPE_ID) form table (1) using the relationship R_1 . For example, as buildings can have different HVAC distribution systems, several DIST_SYS_IDs can have HVAC for their distribution system type. This table also contains description, capacity, and installation date of the distribution systems.

(3) *SPACE* (Space) table: This table includes the data related to all the spaces. As any space may have various distribution system types, all the types such as HVAC_SYS_ID and ELEC_SYS_ID are considered in this table. HVAC_SYS_ID and ELEC_SYS_ID are valued by a DIST_SYS_ID from table (2) using the realtionship R_2, showing the distribution systems related to the spaces. Other data related to spaces such as volume is also considered in this table.

(4) *ELEMENT* (Element) table: This table includes all the elements of a building and defines the spaces they are located in using SPACE_ID from table (3) through the relationship R_4. Relationship R_3, DIST_SYS_ID from table (2) is used in this table to define the elements which belong to a distribution system. For example, as a boiler is a part of an HVAC distribution system of a building, it has a DIST_SYS_ID but a chair does not have any. ELEMENT_TYPE and ELEMENT_CONDITION are other data used in this table.

(5) *WO* (Work order) table: This table includes all the work orders related to elements. In this table, a work order ID is assigned to each element using a WO_ID where ELEMENT_IDs are retrieved from table (4) via the relationship R_5. This table contains the work order type related to each element which is either *Corrective* or *Preventive,* in addition to the year of the work order. WO_STATUS is used to define the work orders status which are *done* or *in process.*

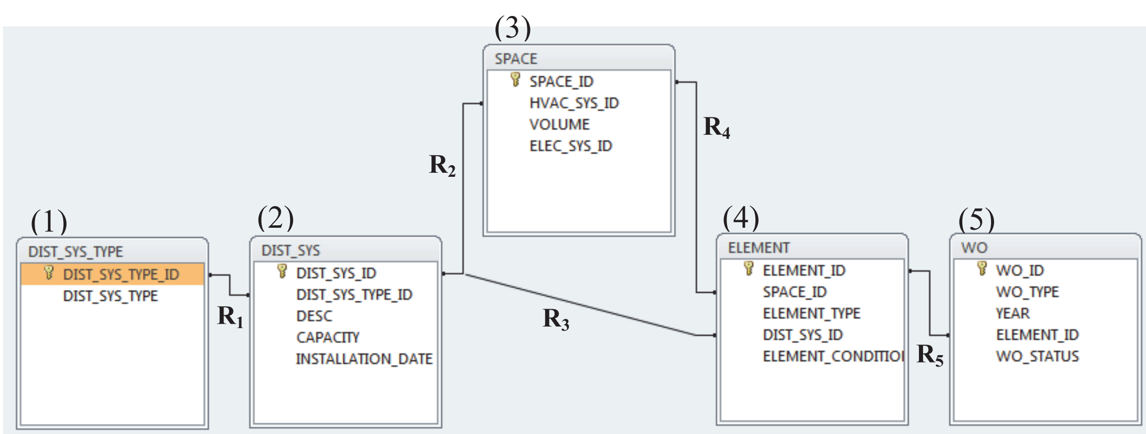


Figure 3-7 Relations between Tables in the Database

Figure 3-8 shows an example query for selecting the HVAC elements servicing space 4, having more than three corrective work orders in year 2008. Similar queries can be used to visualize cause-effect relationships caused by the windows and doors. The query selects the HVAC elements from the relational database (Figure 3-7) through three steps including:

(1) In this step, the query selects all the ELEMENT_IDs from ELEMENT table (table 4) and selects HVAC_SYS_ID (*foreign key* from table 2 in table 3) related to the SPACE_ID = 4 from the SPACE table (table 3). Then, from these selections, the query chooses the ELEMENT_IDs which their DIST_SYS_ID (*foreign key* from table 2 in table 4) is equal to HVAC_SYS_ID of the space 4. Briefly, the query selects all the elements having the same HVAC distribution system as space 4.

(2) In this step, WO table (table 5) is used to select the ELEMENT_IDs (*foreign key* from table 4 in table 5) resulting from step (1) which their work order type is corrective (WO_TYPE = "CORRECTIVE") in the year 2008 (YEAR = "2008"). Briefly, in this step all the elements from step (1) are filtered by having corrective type of work order in year 2008.

(3) In this step, the query counts the number of work orders related to each element resulting from step (2), using the string *Count (WO.ELEMENT_ID)*. Then, it chooses the elements having equal to or more than 3 work orders using the string HAVING (((Count (WO. [ELEMENT_ID])) > = 3)) and group them according to their number of work orders using the string GROUP BY WO.ELEMENT_ID. In the final step, the results are put in a table with two columns. The first column shows the ELEMENT_ID and the second column shows the number of work orders related to each element under CountOfELEMET_ID column. Therefore, the final results of this step are the elements with work orders equal to or more than 3.

```
SELECT WO.ELEMENT_ID, Count (WO.ELEMENT_ID) AS CountOfELEMENT_ID
FROM WO WHERE
(((WO.ELEMENT_ID) In
(SELECT ELEMENT.ELEMENT_ID FROM ELEMENT WHERE ELEMENT.[DIST_SYS_ID] =
(SELECT SPACE.HVAC_SYS_ID FROM SPACE WHERE SPACE_ID=4)))          (1)
AND ((WO.WO_TYPE)="CORRECTIVE") AND ((WO.YEAR)=2008))            (2)
GROUP BY WO.ELEMENT_ID
HAVING (((Count(WO.[ELEMENT_ID]))>=3));                          (3)
```

Figure 3-8 Query of Retrieving the Desired HVAC Components

3.2.4 VISUALIZATION (STEP 4)

Visualization methods

Color coding of spaces or components is an important visualization aid. There are several methods used by different studies to visualize components/conditions/history combined with color coding. These methods include:

(1) Icons/Symbols

This method is usable for the states (e.g. installed and replaced), conditions (e.g. good and bad) or attributes (e.g. humidity). Akcamete et al. (2010) used symbols in their research to show the assets and their conditions where the geometric shapes show the condition of components and the patterns show the components. As the graphical patterns are limited, and there are many components in a building, this visualization method will be complicated and prone to errors for the viewer (Figure 3-9). This method is useful for the visualization of small components.

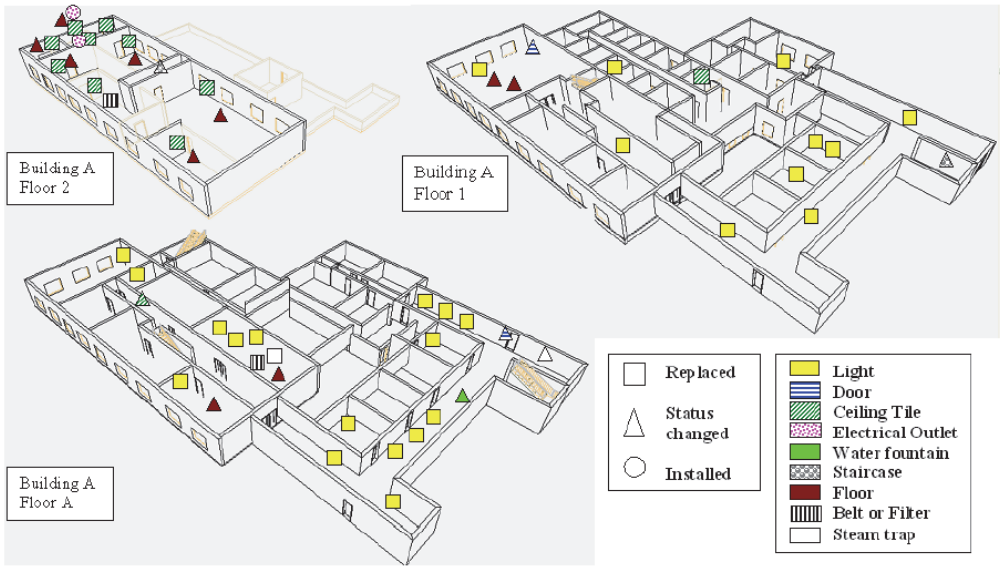


Figure 3-9 Symbols Used to Show Maintenance and Repairs of Components (Akcamete et al., 2010)

(2) 3D Components

Color coding of 3D assets for the visualization of assets conditions during the construction and operation phases is another method. Figure 3-10 shows the visualization of components' status during the O&M phase. The component with green color is already inspected and the components colored in dark pink are waiting to be inspected according to the inspection schedule. The components in orange color have to be replaced. This method is useful for remarkable-sized components such as boilers, cooling towers, chillers, etc. This method is not useful for visualizing small components.

(3) Color-coded Spaces

Figure 3-11 shows the color-coded scheme as another method, to visualize different spaces according to their functionality. This type of visualization is more useful for space management.

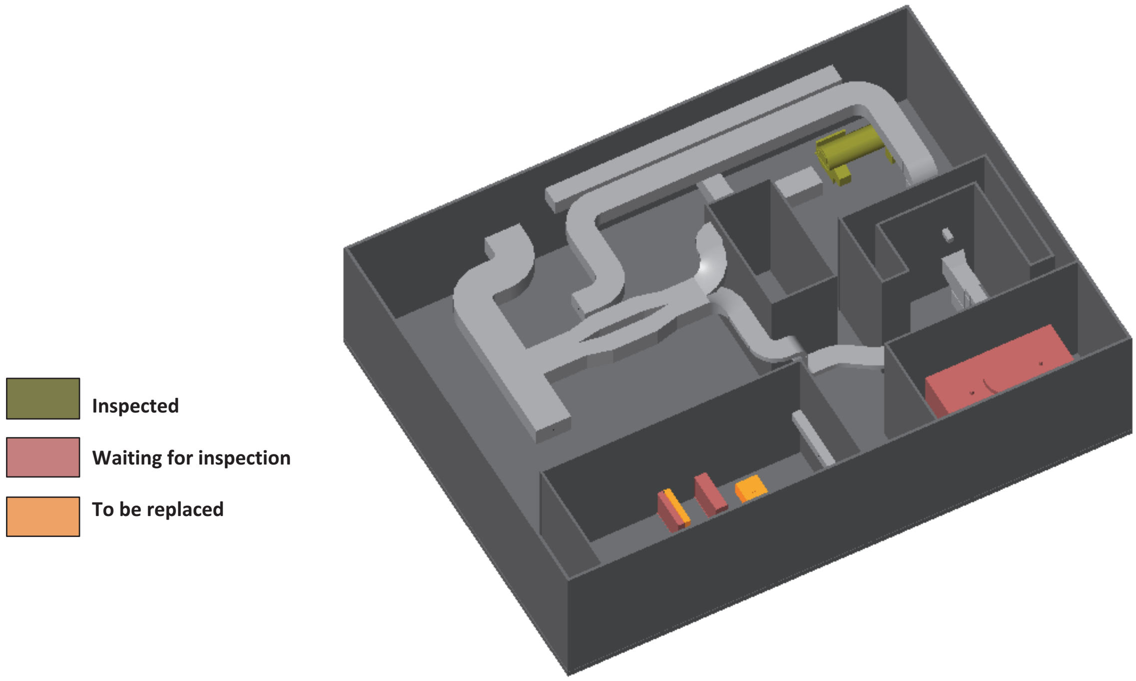


Figure 3-10 HVAC 3D components of One Floor During the Maintenance Phase

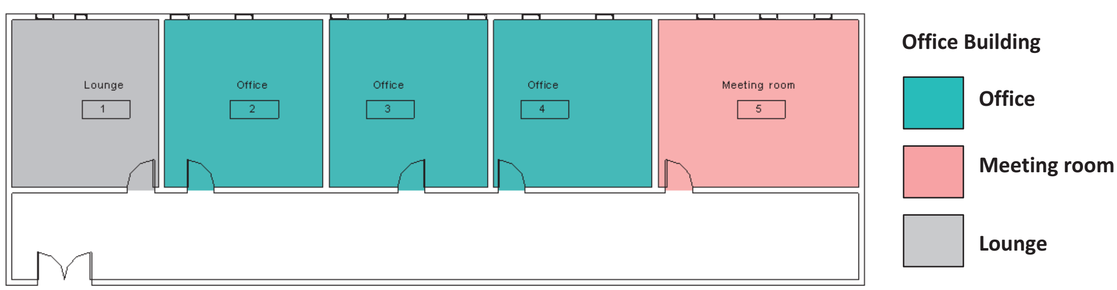


Figure 3-11 Color-Coded Scheme method

Visualization of the results of queries in 3D or 4D

Finally, visualization of the results of queries is done in 3D or 4D. Different analysis including: (a) spatial analysis, (b) temporal analysis, and (c) spatio-temporal analysis can be done using 3D and 4D.

(a) *Spatial analysis:* Figure 3-12 (a) shows an example spatial analysis by visualizing the results of queries in 3D for visual analytics. In this figure, the components with high probability of being the causes of the high temperature problem of a space are identified. Figure 3-12 (b) shows the chiller located in the mechanical room in red and some ducts connected to the chiller in yellow. This figure shows that the chiller and the ducts are in bad and fair conditions, respectively. Figure 3-12 (c) shows the temperature sensor in red with bad condition and two windows in yellow which shows their fair condition. As the result of visual analytics, it can be found that the chiller and the temperature sensor may be the source of the high temperature problem. The components with fair condition should be investigated after those of bad condition as possible cause of the problem. Likewise, visualizing the amount of work orders of heaters located in different spaces helps finding the heater having more problems.

(b) *Temporal analysis:* The amount of work orders changes irregularly during a year because of the difference in the usage amount of spaces and components. Therefore, visualizing the condition of components over time can be used to identify the periods during which a component deteriorated faster than average or has abnormal change in its condition. Temporal analysis helps to identify the maintenance efforts needed for spaces and components at different time periods. The deterioration of components during a period of time is simulated by visualizing the change of condition over time using a 4D model. Figure 3-13 shows the components' conditions in 2008, 2009, and 2010. For example, the chiller has fair condition (yellow) in 2008 and 2009 and bad condition in 2010 (red). It can be interpreted from the simulation that the condition of the chiller deteriorated in 2010. Consequently, performing necessary maintenance can avoid further problems and improve the condition of the unit. This kind of visual analytics can help the facilities manager to compare the conditions of components at different times and to find the periods which components deteriorate abnormally.

(c) *Spatio-temporal analysis:* spatio-temporal analysis can be used to discover cause-effect relationships between different spaces/components over time. Furthermore, several spaces and components with the same functionality can be visualized based on their spatial and logical relationships over time. An example of such visualization is visualizing the amount of hot/cold work orders for different spaces in addition to the amount of work orders of all the components related to hot/cold problems for those spaces over time.

3.2.5 Visual Analytics Procedure in BIM Tools for FM

Visualization of components and spaces based on the number of corrective work orders using pre-defined queries helps discovering cause-effect patterns. Some of these causes are recorded as corrective work orders, e.g. painting and leakage. Some other causes are not recorded as work orders but could be inferred from the visualization of effects and the expertise of the users. For example, in case of availability of painting work orders only, by the visualization of the spaces' painting work orders, the possibility of the existence of a broken pipe in the upper floor can be inferred.

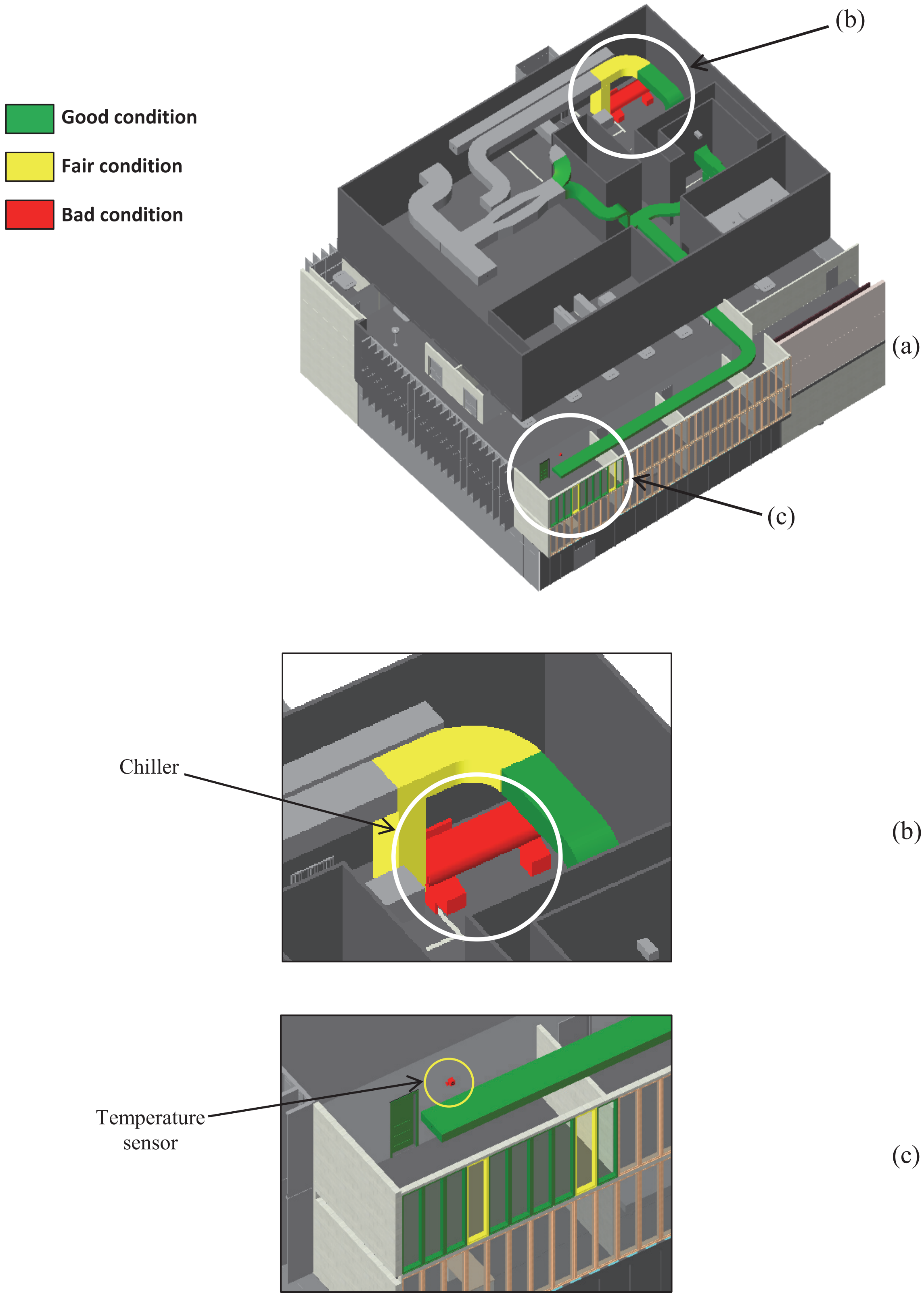


Figure 3-12 Visualization of the Results of the Queries

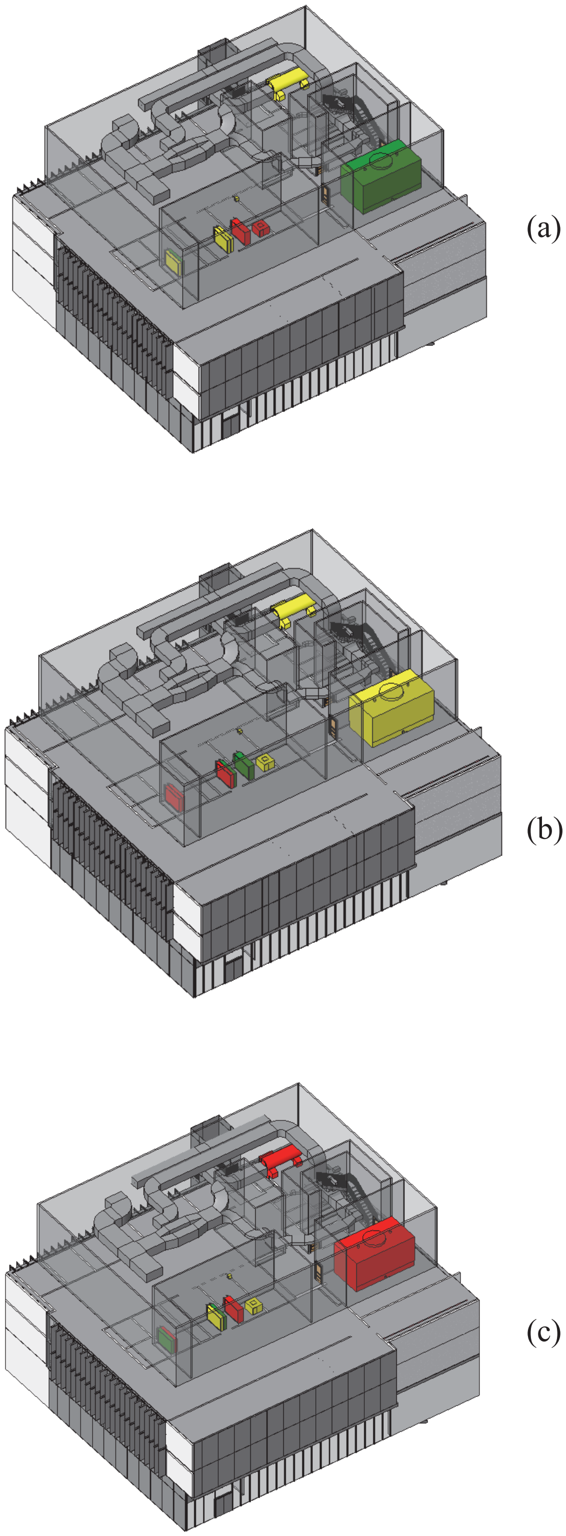


Figure 3-13 Components Condition Visualization in 2008 (a), 2009 (b), and 2010 (c)

Interviews with Concordia Facilities managers are done to define some deterioration/failure cause-effect relationships. The current status of practice relies on the experience and internal communication for cause/effect detection. For example, at Concordia, all shops such as plumbing and electrical, use internal communications to find out the root causes of problems.

Figure 3-14 shows the process of BIM-based integration and visualization of FM data. This process includes:

(a) Define new attributes in the CMMS. These attributes can be used for the visual analytics of the deterioration condition of the components based on cause-effect relationships. For example, these attributes can be defined based on desired time intervals such as the number of work orders or deterioration conditions in 2008, 2009, and 2010.

(b) Define the same attributes in the BIM software that are already defined in CMMS. Most of the BIM-compatible tools have the ability of defining new attribute.

(c) Define visualization configuration in the BIM software. As the visualization will be done in BIM software for visual analytics, these configurations define components' visualization rules.

(d) Map the newly defined CMMS and BIM software attributes. This step is done only once to connect the CMMS to the BIM software. Updating is done automatically for the next times.

(e) Update the CMMS database with corrective or preventive work orders or deterioration conditions. In this step, values of component's attributes are updated by technicians or inspectors.

(f) Define visualization queries to retrieve the desired data. The queries can be defined in the BIM software or the CMMS.

(g) Synchronize the BIM model with the CMMS for updated data from inspection or maintenance work orders.

(h) Run and visualize the pre-defined queries in the BIM tool using the 3D BIM model. In this step, through visual analytics, the main potential causes of a problem are found based on cause-effect relationships.

(i) Export BIM to 4D simulator. BIM model should be exported in a format that keeps the attributes needed for simulation. A 4D simulator is used for adding time to the 3D model for the 4D simulation. The visualized 4D simulation is based on updated data from CMMS.

(j) Define 4D simulation settings in the 4D simulator including the visualization configuration, tasks, and time. If the simulation settings are already defined, this step can be skipped.

(k) Update the 4D model. This step should be done to relate the updated assets to their corresponding data.

(l) Apply the simulation to visualize the 4D model. In order to repeat the process with an updated 4D model, the process can be started from step (e).

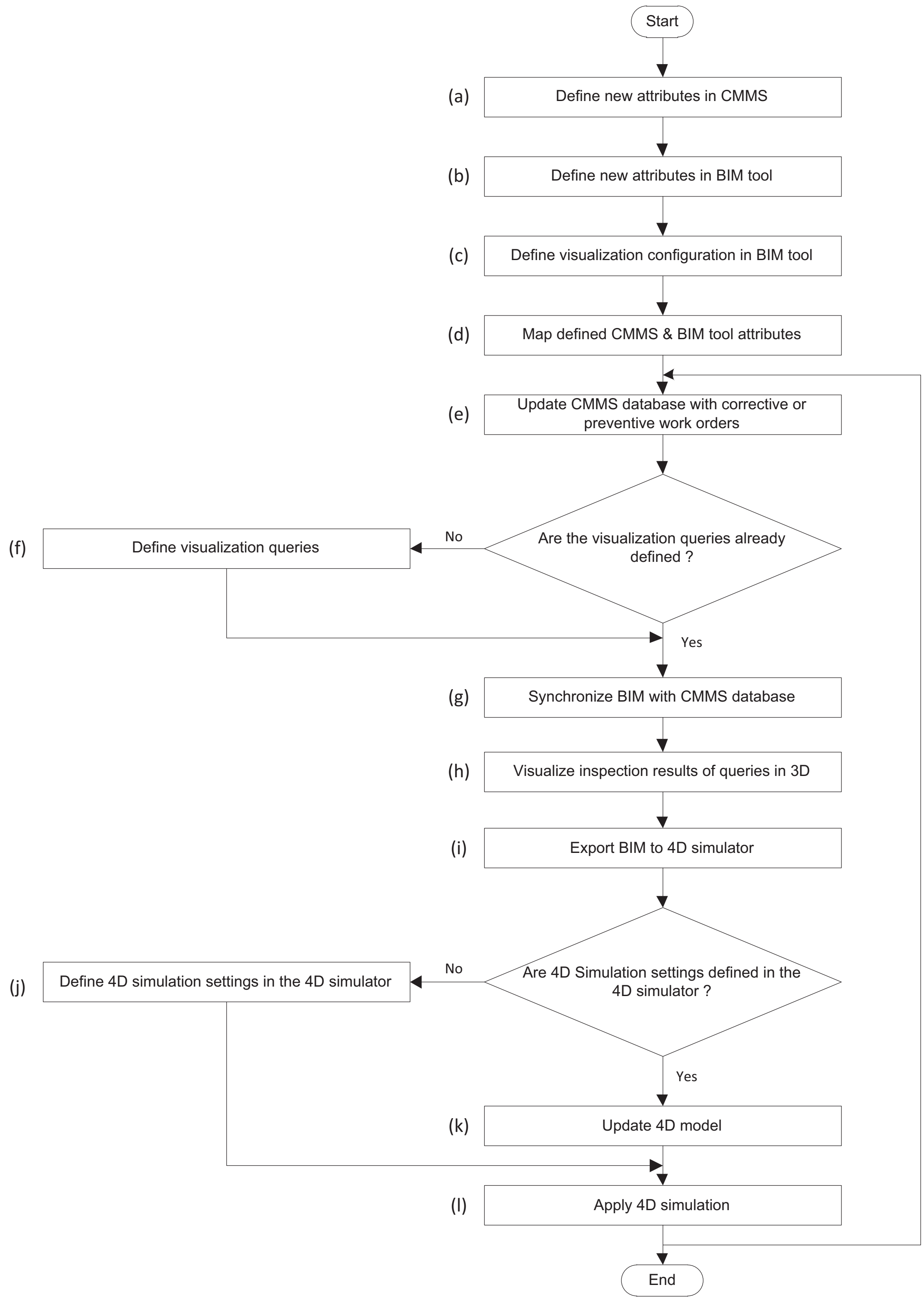


Figure 3-14 Steps of Integration and Visualization of FM Data

3.3 Case study

3.3.1 Introduction

A case study is implemented at Concordia University to demonstrate the validity of the proposed method. In this case study, FM required data from different sources are integrated used on standard formats. In addition, new attributes required for FM, are added to the CMMS and BIM tool. Moreover, the conditions of components are updated to simulate the work done by inspectors and technicians according to the amount of preventive and corrective work orders. Based on a developed database, the components having the possibility of being the cause of temperature problems in a room are visualized in terms of the number of work orders. The updated data from CMMS is retrieved and visualized in the BIM tool using defined queries for visual analytics. In addition, a 4D simulator is used to display the behavior of the components over time in terms of deterioration.

3.3.2 Software Used in the Case Study

FM:Interact

FM:Interact is a CMMS and composed of some modules such as space management, asset management, and facilities maintenance. FM:Interact is a web-based tool that allows organization-wide access to facilities data. Asset management module is used for the tracking of assets such as furniture, equipment, computers, life safety systems, building systems, and art works (FM:Systems, 2011). A collection of related tables in the facilities maintenance module is used to define our queries in the proposed approach.

FM:Interact can be connected to Autodesk Revit, which is a BIM compatible software, through FM:Interact's add-in in Revit.

Autodesk Revit

Revit is a software for BIM implementation in the AECOO industry. Revit allows defining new attributes for components and also supports the customization of the predefined components. Moreover, as a platform, it also has a large set of associated applications. Revit Architecture, Revit Structure, and Revit MEP are different software of Autodesk supporting IFC (Autodesk, 2011). It is also possible to add COBIE2 related data to the model in Revit. Figure 3-15 shows an example of adding COBIE2 data of a boiler in Revit.

Autodesk Navisworks

Autodesk Navisworks is used to develop the 4D model. Although it supports IFC, Revit files can be also exported to Navisworks using the NWC format directly from Revit. In order to increase the quality of FM, electronic documents such as manuals can be linked to the components through Autodesk Navisworks. In addition, Navisworks has useful features such as clash detection and version comparison (Autodesk, 2011).

3.3.3 IMPLEMENTATION

The Genomics research center of Concordia University is used in this case study. As the Genomics research center was not commissioned completely, the COBIE data were not available for this case study. In order to show the feasibility of the proposed method, the number of work orders related to components in three consecutive years (2008 to 2010) have been assumed. The architectural and mechanical models are generated in Revit Architecture 2011 and Revit MEP 2011, respectively. The 3D BIM model is created based on 2D drawings, provided by the FM department of Concordia University, as there was no BIM model available for this building.

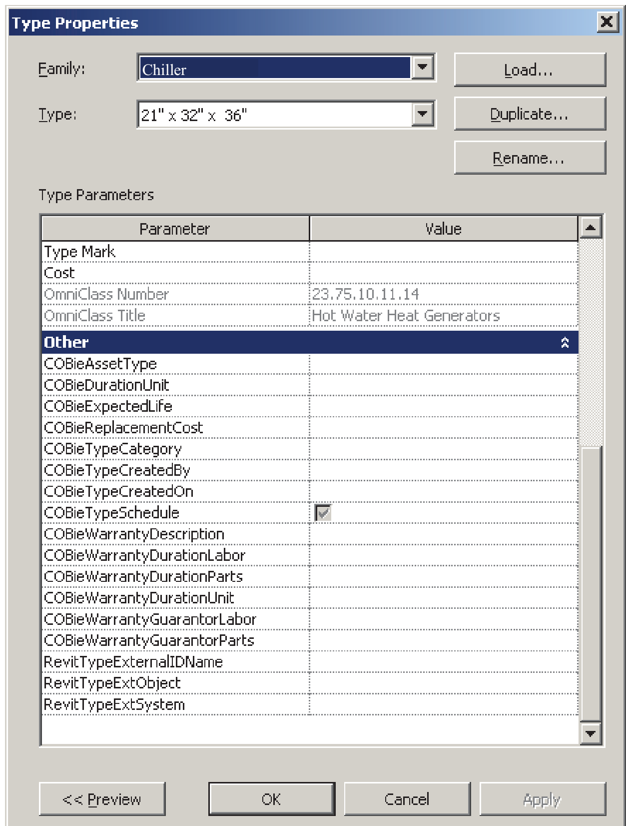


Figure 3-15 Revit Type Properties Window for Adding COBIE2 Data of a Chiller

The steps of the integration and visualization of FM data, shown in Figure 3-14**,** are explained in detail in the following:

(a) Define new attributes in CMMS

As shown in Figure 3-16, *Condition 2008*, *Condition 2009*, and *Condition 2010* are newly defined attributes in FM:Interact, showing the conditions of components in year 2008, 2009, and 2010, respectively. These new attributes are used in the 4D simulation of the components’ conditions over time. In addition, COBIE2 data are defined as new attributes in FM:Interact. Other attributes such as spatial and logical relationships between components and spaces can be also added to FM:Interact.

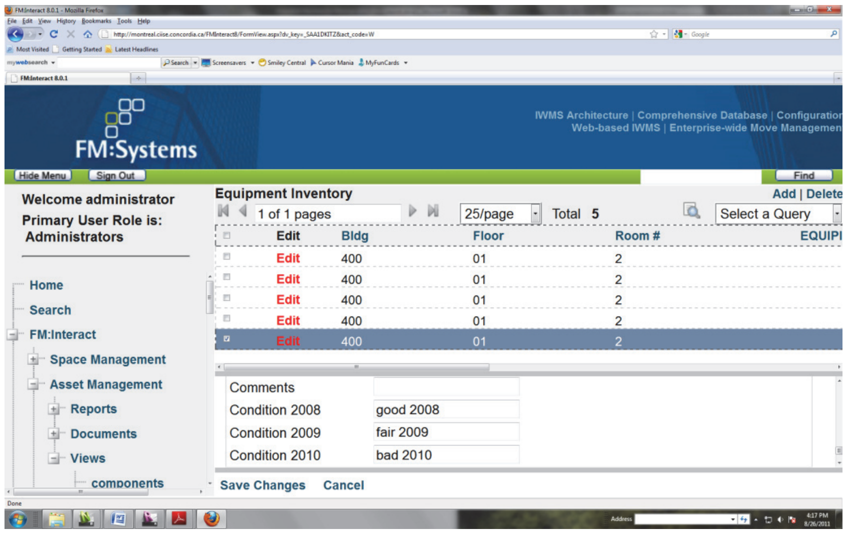


Figure 3-16 New Properties Defined in FM:Interact for Mechanical Components

(b) Define new attributes in BIM software

Figure 3-17 shows the definition of *Condition 2008*, *Condition 2009*, and *Condition 2010* in Revit that are already defined in FM:Interact. Revit has categorized components into different family types such as mechanical equipment, wall, window, etc. In Revit, components have two kinds of properties: *Type properties* and *Instance properties*. *Type properties* are common between all components of a specific family, which means that a change of the value of an attribute of an instance affects all current and future instances of that family. The attributes defined as *Instance properties* allow adding a different value to each instance separately. The new attributes in Revit are defined as *Instance properties* of the components. Good, bad, and fair are considered as the components’ conditions.

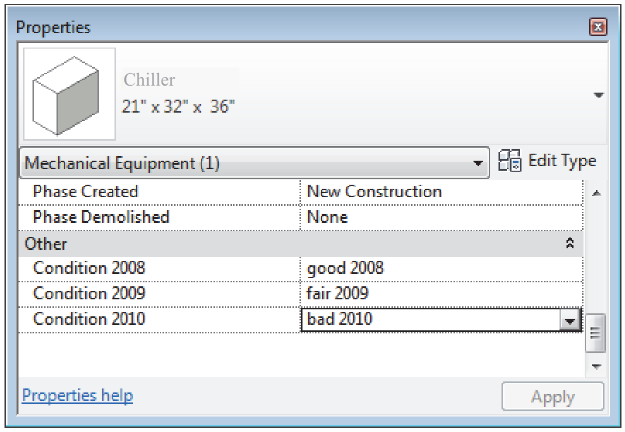


Figure 3-17 New Properties Defined in Revit for Mechanical Components

This mechanism is used mainly for visualizing construction tasks in 4D. However, in this research, this concept is used for visualizing the components' deterioration conditions over time. Therefore, deterioration condition data is linked to the components. As all the components are interrelated to their corresponding data in the 4D simulator for temporal analysis, the values of the attributes should be unique. For this matter, the year of inspection is added to the condition value (e.g. *good 2008* for good condition in year 2008 or *fair 2010* for fair condition in year 2010).

(c) Define visualization configuration in BIM tool

Visualization configuration is defined in Revit to visualize the results of the queries. "Colored 3D components" is used as the visualization method in this case study. The components with good, fair, or bad conditions are defined to become green, yellow, or red, respectively

.

(d) Map defined CMMS & BIM tool attributes

As shown in Figure 3-18, the newly defined attributes are mapped between FM:Interact and Revit through FM:Interact add-in in Revit. The updated components' conditions will be reflected in Revit through synchronization of FM:Interact and Revit.

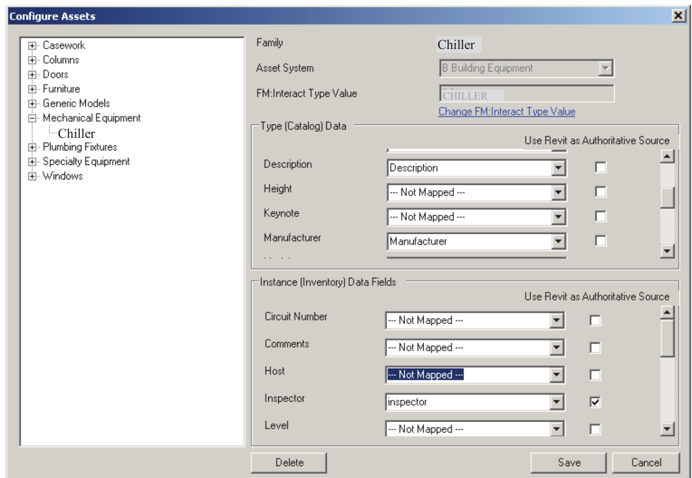


Figure 3-18 Mapping Components' Attributes Between FM:Interact and Revit

(e) Update the CMMS database with corrective or preventive work orders

Corrective and preventive work orders are usually done by technicians and inspectors. For this matter, the database of FM:Interact should be updated by technicians or inspectors with corrective or preventive work orders in order to have reliable results. As mentioned previously, the number of work orders can be transformed into a condition that can be used to identify the components with high possibility of being the source of problems.

(f) Define visualization queries

All the components that can cause temperature disorder related to a specific room (e.g. SPACE_ID=4) at year 2008 are defined, where components with less than three, equal to or more than three, and zero number of work orders are assumed to be in fair, bad, and good conditions, respectively.

(g) Synchronize BIM with CMMS database

The updated data in FM:Interact are reflected in Revit for visualization. This step is done through the installed FM:Interact add-in in Revit. The synchronization can be done automatically as soon as FM:Interact database is updated.

(h) Visualize inspection results of queries in 3D

The results of the queries are used to visualize the components related to the same space in terms of the number of work orders. Different colors are defined for different ranges of number of work orders. As shown in Figure 3-12, the chiller located in the mechanical room (serving room 4) and the temperature sensor located in the same room are shown in red color. The red color indicates bad condition based on the number of work orders. The door and most of the windows are shown in green and two windows are shown in yellow which means they have good and fair conditions, respectively as shown in Figure 3-12.

(i) Export BIM to 4D simulator

Navisworks is used for adding the time to the 3D BIM model for 4D simulations. In this step, components' conditions over time are visualized. The 4D simulation is based on the updated work orders data from the CMMS. IFC and NWC are the formats used to export the 3D model from Revit to Navisworks. *Autodesk Navisworks 2011 NWC file exporter* is an external plug-in to export the Revit file in NWC format to Navisworks (Autodesk, 2011).

(j) Define 4D simulation settings in the 4D simulator

The *TimeLiner* window of Navisworks is used to define the schedule and the simulation configuration. This window has *Task, Links, Gantt view, Configure, Rules,* and *Simulate* tabs (Autodesk, 2011). The *Tasks* tab is used to define the schedule. We can either use *Links* tab from *Timeliner* window to import a schedule from other scheduling software such as Microsoft Project, Asta, and Primavera or do the scheduling using the *Tasks* tab of the *timeliner* window (Autodesk, 2011). Gantt view shows the schedule in a bar chart format. Task types are defined first in the *configure* tab to be assigned to the tasks in the Tasks tab which is displayed in Figure 3-19. Each task type can be assigned to many tasks. Task types define how tasks will be visualized in the simulation in terms of color. Green, yellow, and red are defined as the colors for good, fair, and bad conditions, respectively.

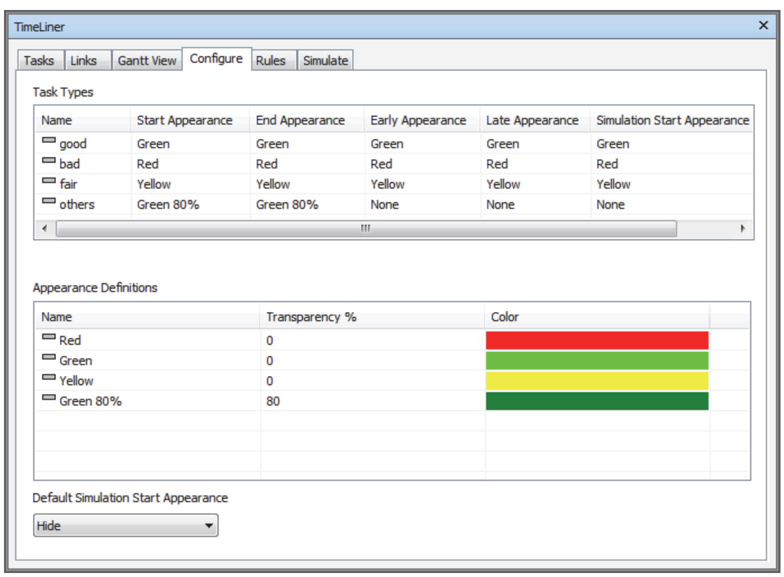


Figure 3-19 Configure Tab

Navisworks maps the tasks' name to the components having the same name as one of their properties value (Autodesk, 2011). This setting is done through *Rules* tab to avoid attaching components to the tasks manually. We have defined three rules to map the components to the tasks manually. The rules are based on the new attributes already defined in FM:Interact and Revit. The Revit file exported to navisworks carries these new properties and their values. Properties of each component in Navisworks are divided to some categories. Figure 3-20 shows the properties of a mechanical component categorized to Item, Element, Level, etc.

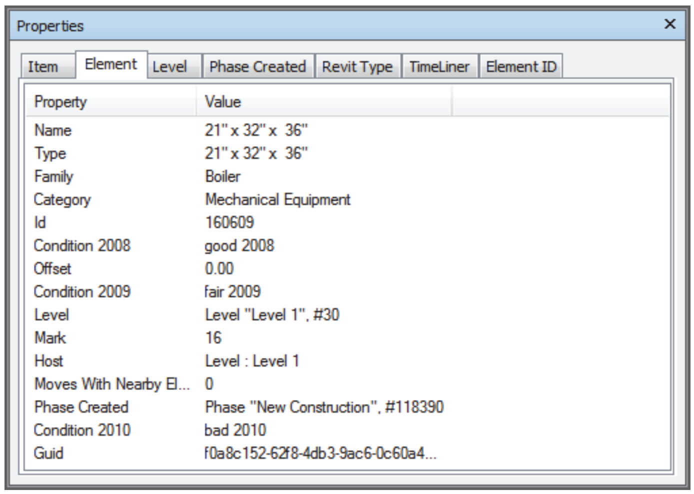


Figure 3-20 Properties of a Mechanical Component in Navisworks

As shown in Figure 3-21, *rule description* is used to define the rules. Matching is chosen for case sensitivity so only matched names that are exactly the same will be selected. *Condition 2008* is a rule defined to attach the components' condition in year 2008 to their corresponding tasks. The element tab then is chosen as the category and *Condition 2008* as the property. On the other hand, we should define tasks with the exact name of the properties' values. E.g. "good 2008" is the value of *Condition 2008* property for a mechanical component. A task should be defined with the exact name of "good 2008". The final representation of the rule *Condition 2008* would be: "*Map TimeLiner Tasks* *from Column **Name** to Items with the property with Category **Name** **'Element'** and Property **Name** **'Condition 2008'**, **Matching** case".*

The rule *Condition 2008* will attach all the components having "good 2008" as their condition for year 2008 to the "good 2008" task and simulate them in green color for year 2008. Condition 2009 and 2010 rules are defined in the same way.

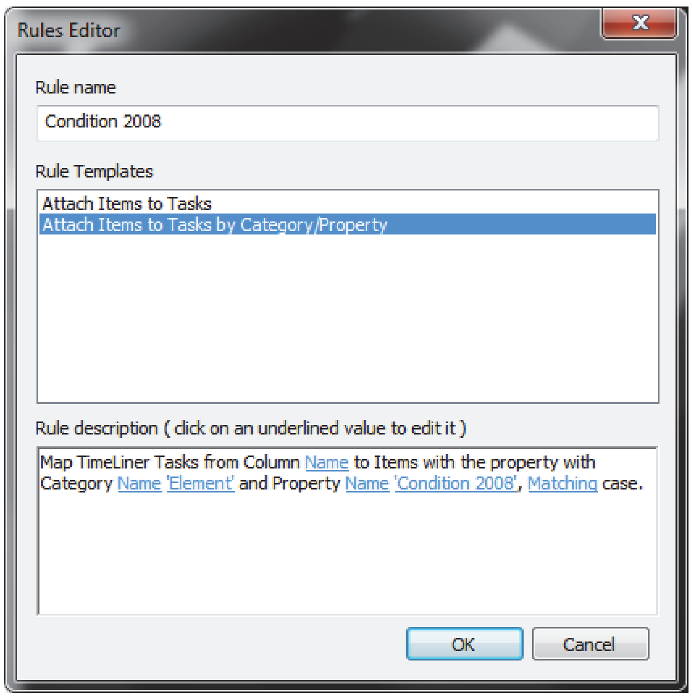
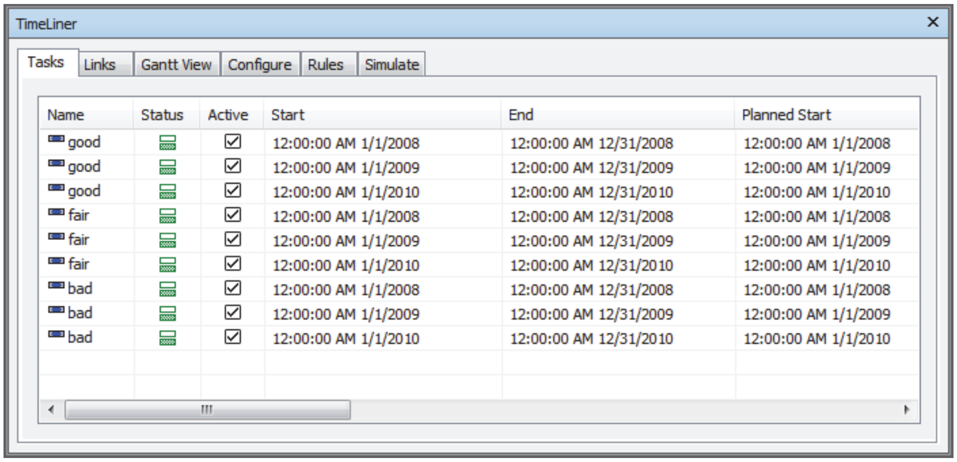


Figure 3-21 Rules Editor in Navisworks

(k) Update the 4D model

The rules defined in the previous step are used to automate the mapping so that as soon as the model in Revit gets updated, all the tasks will be mapped to their relevant components.

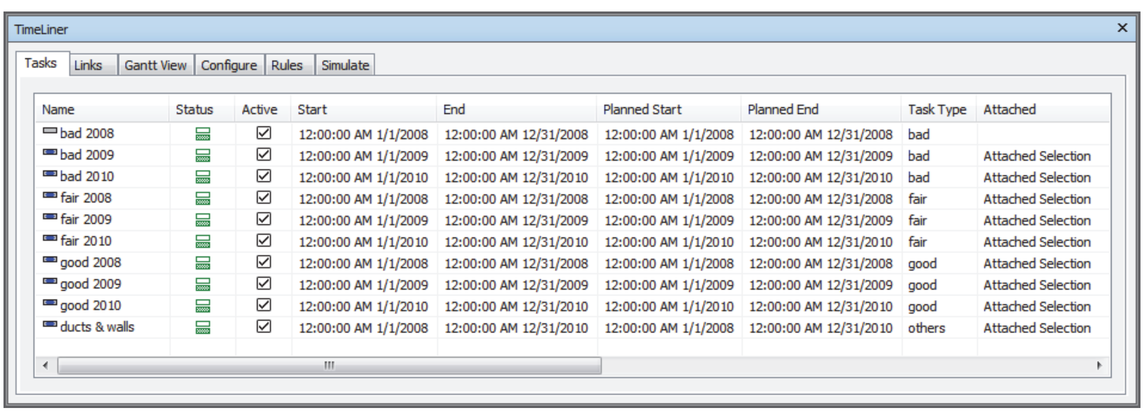
As we are doing the simulation for years 2008, 2009, and 2010 and we have good, fair and bad conditions for the components, we have to define nine tasks. In the first test we defined nine tasks, but we did not consider the year in both the tasks' names and the properties values (Figure 3-22). This test was not successful because in the simulation of year 2009, all the components with good condition for 2008, 2009, and 2010 became green as time was only defined as a string in the properties values which Navisworks cannot recognize.



Name	Status	Active	Start	End	Planned Start
good		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	12:00:00 AM 1/1/2008
good		☑	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	12:00:00 AM 1/1/2009
good		☑	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2010
fair		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	12:00:00 AM 1/1/2008
fair		☑	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	12:00:00 AM 1/1/2009
fair		☑	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2010
bad		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	12:00:00 AM 1/1/2008
bad		☑	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	12:00:00 AM 1/1/2009
bad		☑	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2010

Figure 3-22 Tasks with no Unique Names but Different Times

As the name of the tasks and the values of the properties must be unique, good 2008, fair 2008, bad 2008, good 2009, fair 2009, bad 2009, good 2010, fair 2010, and bad 2010 are defined as the tasks and are used for the values of the properties (Figure 3-23).



Name	Status	Active	Start	End	Planned Start	Planned End	Task Type	Attached
bad 2008		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	bad	
bad 2009		☑	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	bad	Attached Selection
bad 2010		☑	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	bad	Attached Selection
fair 2008		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	fair	Attached Selection
fair 2009		☑	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	fair	Attached Selection
fair 2010		☑	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	fair	Attached Selection
good 2008		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2008	good	Attached Selection
good 2009		☑	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	12:00:00 AM 1/1/2009	12:00:00 AM 12/31/2009	good	Attached Selection
good 2010		☑	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2010	12:00:00 AM 12/31/2010	good	Attached Selection
ducts & walls		☑	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2010	12:00:00 AM 1/1/2008	12:00:00 AM 12/31/2010	others	Attached Selection

Figure 3-23 Unique Names for the Tasks and the Properties Values

(l) Apply the 4D simulation

In this step, the 4D simulation is applied to simulate the update 4D model in Navisworks as shown in Figure 3-13.

Discussion

Levels of applying the proposed method can be explained as the following:

(1) *Text-based analysis:* In the current FM practice, analysis can be done based on text-based work orders data where visualization is not used for analysis.

(2) *3D-based analysis:* 3D visualization for spatial analysis can be done if the CMMS is already linked with BIM tool.

(3) *4D-based analysis:* 4D visualization for temporal analysis can be done if the CMMS has condition history based on inspection or work orders.

The proposed method can be used to identify the potential problems based on cause-effect relationships at several locations.

3.4 SUMMARY AND CONCLUSIONS

The proposed approach initially showed the possible ways for integrating COBIE data with CMMS and BIM tools to increase the efficiency of O&M phase in terms of the correctness and completeness of the required data for FM. Then, different kinds of relationships between components and spaces were defined (i.e. logical and spatial) and their corresponding IFC definitions were investigated. Furthermore, the cause-effect relationships between components and spaces were discussed and it was proposed to use a relational database and queries to retrieve the desired data. Cause-effect relationships for temperature problems of a space were studied as an example and an example query was defined to retrieve the needed data for visual analytics.

The conclusions of this research are: (1) In order to have a comprehensive database for FM, it is necessary to integrate data from COBIE and CMMS with the BIM of the facility. The proposed methodology provides different methods for the integration of COBIE data with CMMS to create a comprehensive BIM database encompassing COBIE data and feeding CMMS and BIM tools. However, COBIE data should be required in the contracts to be provided to the owners by the contractors. It is impractical and inefficient to develop COBIE data in the commissioning phase; (2) The proposed visual analytics provides powerful tools for 3D and 4D visualization of the possible causes of problems in a building. To realize this method, this research first defines the spatial and logical relationships between components and spaces. Some of these relationships (i.e. spatial relationships) are already imbedded in the IFC model and can be mapped into relationships in a database; while other relationships (i.e. logical relationships) have to be added to the database; (3) It is important to define a set of queries in the relational database based on cause-effect relationships extracted from the literature and from FM domain experts. These queries use the spatial and logical relationships between components and spaces and will eventually form a knowledge base for visual analytics; and (4) The case study shows the feasibility of the proposed visual analytics method using available CMMS and BIM tools.

This research also identifies the limitations in terms of data and tool. In the case study, the building had not been commissioned completely and the FM department could not provide us with the COBIE data of the Genomics research center. The complete COBIE data could support the case study more comprehensively. The case study showed the need for more standardization of BIM and CMMS tools in addition to more development of BIM and IFC. Tools are needed to apply the defined relationships according to IFC standard. As BIM is not yet developed in its full shape, several inspection and maintenance related data need to be added to BIM for the full implementation of the proposed method.

CHAPTER 4 AUGMENTED REALITY BASED VISUALIZATION OF CONSTRUCTION AND RENOVATION OPERATIONS

4.1 INTRODUCTION

This chapter proposes a new approach based on Augmented Reality (AR) to visually fuse the data from different sources including a BIM, video monitoring, and a Ultra Wide-Band (UWB) Real Time Location System (RTLS). The proposed method can be used to better visualize construction and renovation operations and to retrieve information about the time, space, and activities of a construction or renovation project. The benefits of the data fusion from different resources are discussed in terms of quality and productivity of the project.

4.2 PROPOSED METHOD FOR AR-BASED CONSTRUCTION AND RENOVATION OPERATIONS VISUALIZATION

Visualization of construction and renovation operations increases the quality of FM. For the visualization of assets' construction and renovation operations, it is proposed to attach UWB tags to workers and equipment that are going to be monitored in the building. The UWB RTLS records the tags' IDs and locations with the timestamps when the data was collected. Video cameras are installed at specific locations for monitoring purpose. A video camera records the activities within specific duration, where each video frame has a time stamp. For simplification, it is assumed that there is only one fixed camera used for monitoring one area, e.g., a room. Multiple cameras with pan-tilt-zoom functions can be used to extend the view of the video monitoring. Moreover, moving cameras such as cameras attached to tablet PCs can be used by the facilities managers to monitor the operations progress. Meanwhile, it is assumed that an as-planned BIM model is available, which includes the 3D environment model, task schedule, and resource allocation. Related to the task schedule, another resource database is also available, which indicates the resources needed for specific tasks in terms of labor, equipment, and materials. Worker IDs, equipment IDs, and other attributes are stored in the database, such as the name of the subcontractor company, type of trade, wage of workers, rental cost and capacity of equipment, etc. Each of these different data sources includes only part of the task, space, and time information, which need to be fused to form an integrated database.

In this approach, data from different sources are fused. The locations of workers and equipment are shown with a specific update rate (e.g., 1 Hz) in the BIM model. Videos are embedded in the model by creating virtual cameras in the BIM environment and linking them to the real cameras installed in the area. The BIM model includes a 3D model of the environment, schedule of construction and renovation operations, and the task IDs. In case of renovation, the CMMS can be linked to the BIM model indicating the resource allocation for each task, for example, the number of workers involved in carrying out the task and the type and number of equipment used. Using the integrated database resulting from data fusion, queries can be made to retrieve the information of time, space and events of construction and renovation operations. For example, a query can be formulated to retrieve the video frames containing certain workers or equipment during a specific period for AR. The input of the query is the IDs and the time period, while the output is the relevant video frames. This type of queries can be used for claim arbitration to investigate the specific workers or equipment involved in a certain conflict.

Another type of queries can be used to retrieve the IDs of all workers or equipment and the corresponding video frames during a specific period. The input of a query of this type is the time duration, while the output is the IDs and video frames. Figure 4-1 shows the integration of BIM as a database, information related to construction and renovation operations schedule, workers IDs, and data collected from UWB RTLS and video frames. Data can be fused then for AR visualization of renovation and repair activities. The application of AR visualization can be useful for quality assurance as will be explained in Subsection 4.3.

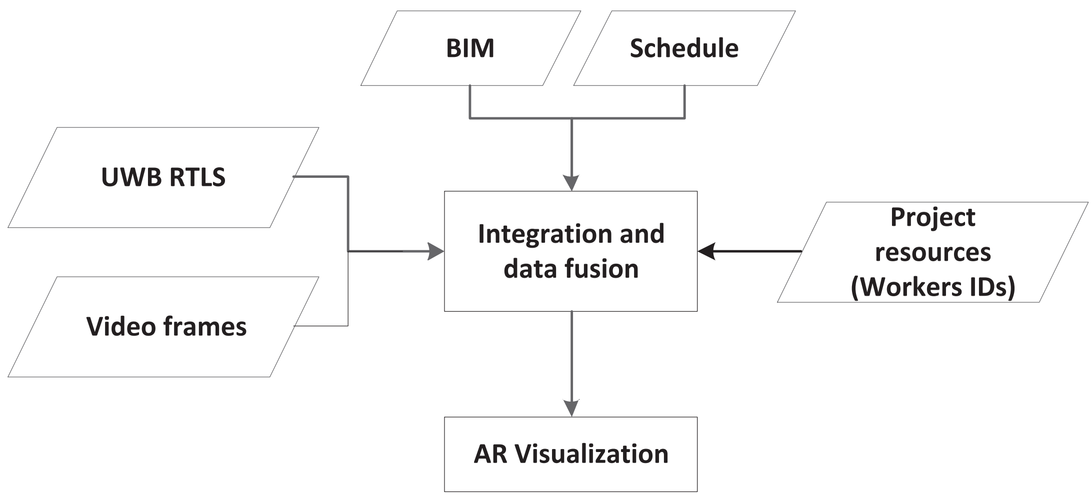


Figure 4-1 Conceptual Framework for AR Data Fusion

The process of fusing the required data from the BIM database is done through six steps as shown in Figure 4-2:

(a) Loading the 3D model of the space which is going to be monitored.

(b) Adding a virtual camera in the 3D model by using the location P_0 (x_0, y_0, z_0) and orientation of the actual camera. The orientation can be found by measuring another point P_1 (x_1, y_1, z_1) on the center line of the camera and taking the vector $P_0 P_1$. These two points can be measured using the UWB system by attaching two tags to the camera.

(c) Adjusting the Field of View (FOV) of the virtual camera according to the FOV and focal length of the actual camera. As shown in Figure 4-3 (Wikipedia, 2011), *v* and *h* are the height and width of camera frames, respectively. *f* is the effective focal length which, at infinity focus, is equal to the focal length of the lens (*f*=F). The horizontal and vertical FOVs(α_h and α_v) of the camera can be obtained using Equations 4.1 and 4.2. The FOVs of the BIM software camera (α'_h and α'_v) should be bigger than those of the actual camera (e.g. 1.2 times) to show parts of the virtual model surrounding the picture.

$$\alpha_{\mathrm{h}} = 2\ \tan^{-1}\left(\frac{\mathrm{h}}{2\mathrm{f}}\right) \quad (4.1)$$

$$\alpha_v = 2\ tan^{-1}\left(\frac{v}{2f}\right) \quad (4.2)$$

(d) Adding a screen, on which the video frame will be displayed, perpendicular to the virtual camera center line. The distance of the screen from the camera can be obtained by calculating the nearest intersection of the shape representing the pyramid of the FOV of the camera with the boundary of the space. Figure 4-3 shows an example of locating the screen in 2D at a distance *d* from the camera location P_0.

(e) Adding the video frame to the screen so that by rendering the pre-defined view in the BIM software, the as-planed and as-built conditions, which are overlapped, can be compared as will be demonstrated in the case study. The picture is made transparent on top of the 3D model to make the comparison possible.

(f) Adding the traces of moving objects (i.e. workers and equipment), captured by the UWB system, to the model. Furthermore, some of the attributes of the moving objects can be displayed on top of the video at a specific location obtained from tracking. For example, the ID of the workers or the type of equipment can be added to augment the scene with information about the moving objects. This integration of UWB data with the 3D model needs applying a transformation matrix (translation, rotation, and scaling) between the two coordination systems of the UWB system and the 3D model.

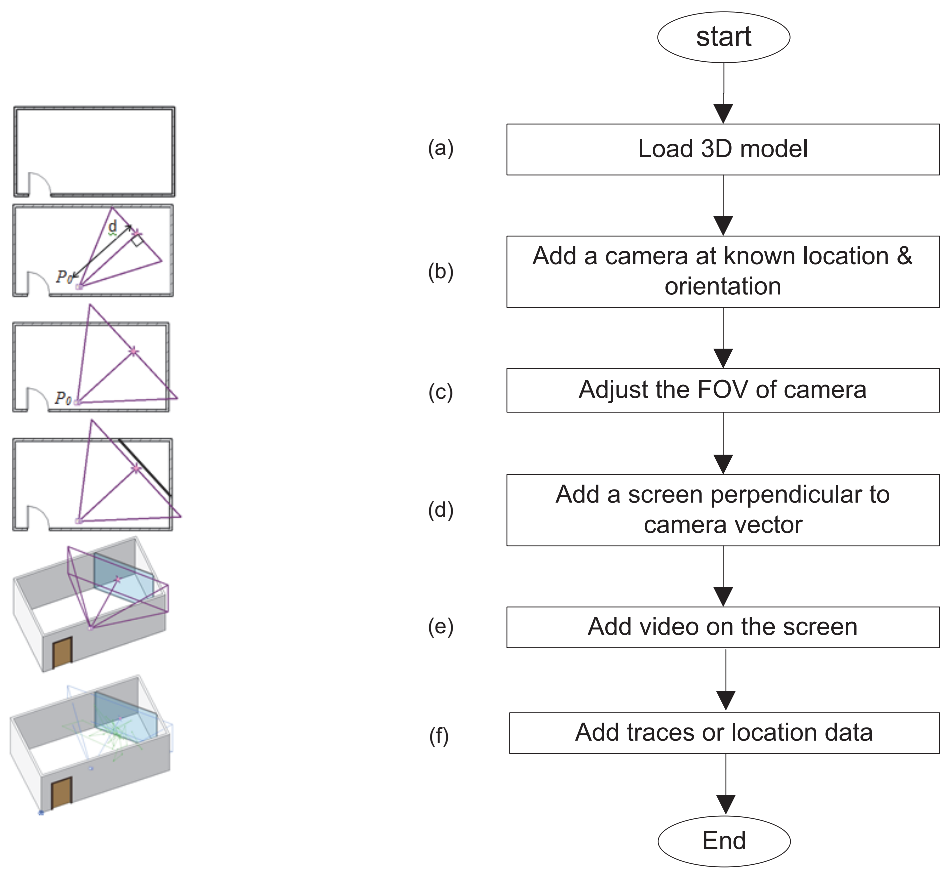


Figure 4-2 Steps of the Proposed Approach for AR

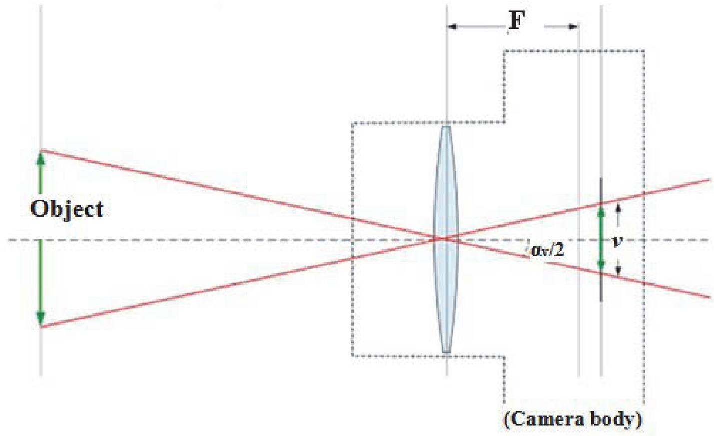


Figure 4-3 FOV and Focal Length of a Camera (Adapted from Wikipedia, 2011)

4.3 CASE STUDIES

4.3.1 INTRODUCTION

The case studies use AR technology by fusing data from BIM and other sources to monitor the construction and renovation operations such as installing HVAC ducts or installing shelves on a wall. AR provides construction and facility managers with an accurate comparison between as-planed and as-built status of the activities.

4.3.2 VISUALIZING CONSTRUCTION AND RENOVATION OPERATIONS USING AR

These case studies are done to visualize the construction and renovation. The models of two existing spaces have been developed in Revit Architecture 2010 to provide the as-planed conditions. Ubisense sensors are used as the UWB system to capture location and orientation of the actual camera in addition to the traces of the workers. An interface is developed to import UWB data to Revit using Revit and Ubisense APIs. A fixed Canon camera FOV is used to take photos of construction progress. Currently, only pictures captured from the camera are integrated into the BIM model. However, the same technique can be applied to videos in the future. By using Equations (1) and (2) from section 3.3, the horizontal and vertical FOVs of the actual camera can be obtained and used to adjust the Revit camera. A 35 mm camera with a normal lens can have up to 50 mm focal length. The frames of the 35 mm cameras are 36 mm × 24 mm. The Revit camera's FOV is 50 degree by default as shown in Figure 4-4. The FOV and effectively the focal length of the Revit camera can be obtained according to Equation 4.3 (Pacific, 2011).

$$\text{Focal length} = \frac{0.5 \times \text{film dimension}}{\tan\left(\frac{\text{FOV}}{2}\right)} \qquad (4.3)$$

By keeping the Revit camera's default settings, the Revit camera is equivalent to a 38.6 mm focal length lens (Pacific, 2011).

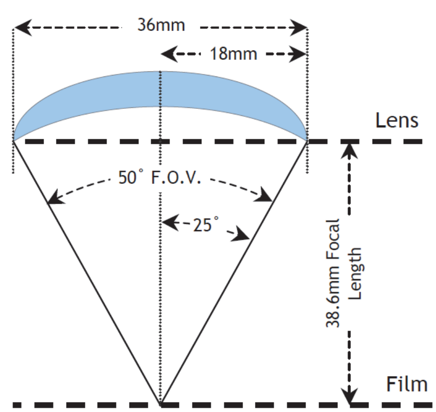


Figure 4-4 The Default Revit Camera's Focal Length (Pacific, 2011)

In the first case study, a room with 3m height, 4m width, and 7m length is modeled in Revit Architecture 2010. Figure 4-5 shows the floor plan of the room and the connections between four sensors. The solid lines show the data cables connecting the sensors with the Power over Ethernet (PoE) switch, whereas the dotted lines show the timing cables. The installation of wall shelves is monitored in this case study. The camera is used to take photos of the installation progress and provide the as-built condition. The real camera is oriented toward the part to be monitored. Data related to the location and orientation of the actual camera is applied in Revit Architecture to define the location and orientation of the Revit camera. Figure 4-6 shows the picture taken by the camera on top of the virtual model.

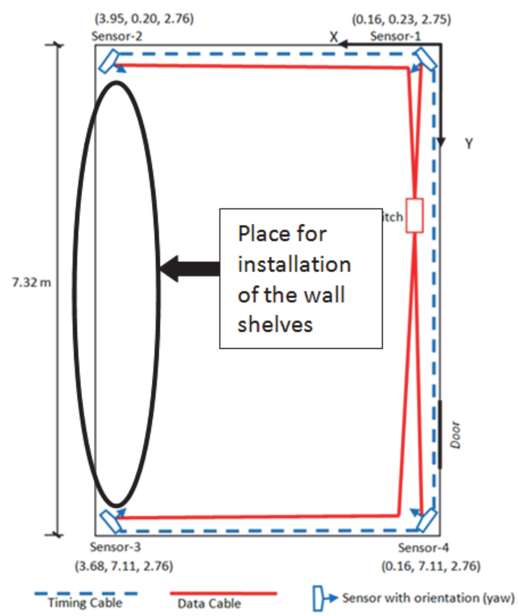


Figure 4-5 Floor Plan of the Room and the Setting of the UWB System

The second case study is used to demonstrate the proposed approach focusing on the tasks of installing HVAC ducts on the 7th floor of the JMSB Building of Concordia University as shown in Figure 4-7. A BIM model of the floor and the ducts has been developed using Revit Architecture and Revit MEP, respectively. The installation work in one part of the floor has been monitored with a video camera and two workers in that part have been tracked using an UWB system.

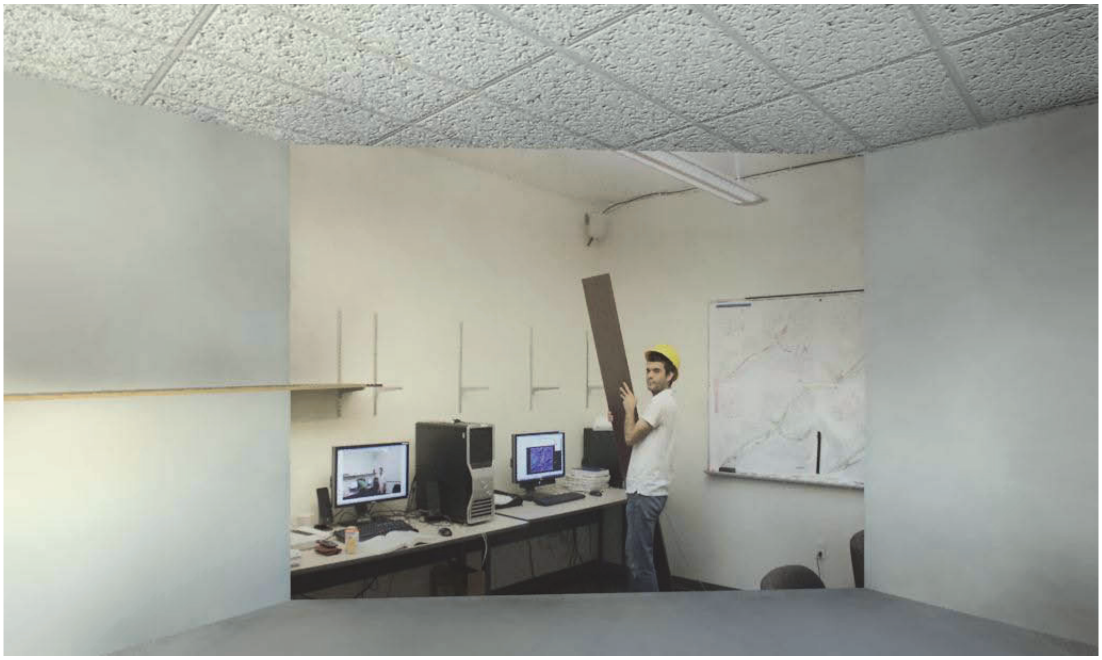


Figure 4-6 Augmented Reality View of the Task of Shelves Installation

The information of BIM, the video monitoring and the UWB traces are processed as follows: (1) The BIM model is used to provide a spatial reference and to show the ducts that have been already installed and those that will be installed in the next few hours using different colors; (2) The pose of the virtual camera within the BIM software is adjusted to match the pose of the actual camera; (3) The collected traces of the movements of the workers are processed to fit over the scene; and (4) The current locations of the workers as identified in the UWB data are used to augment the scene with information about the workers and their planned tasks.

Figure 4-8 shows the floor plan of the construction site modeled in Revit. The red colored ducts show the installed part and the rest parts are going to be installed according to the schedule.

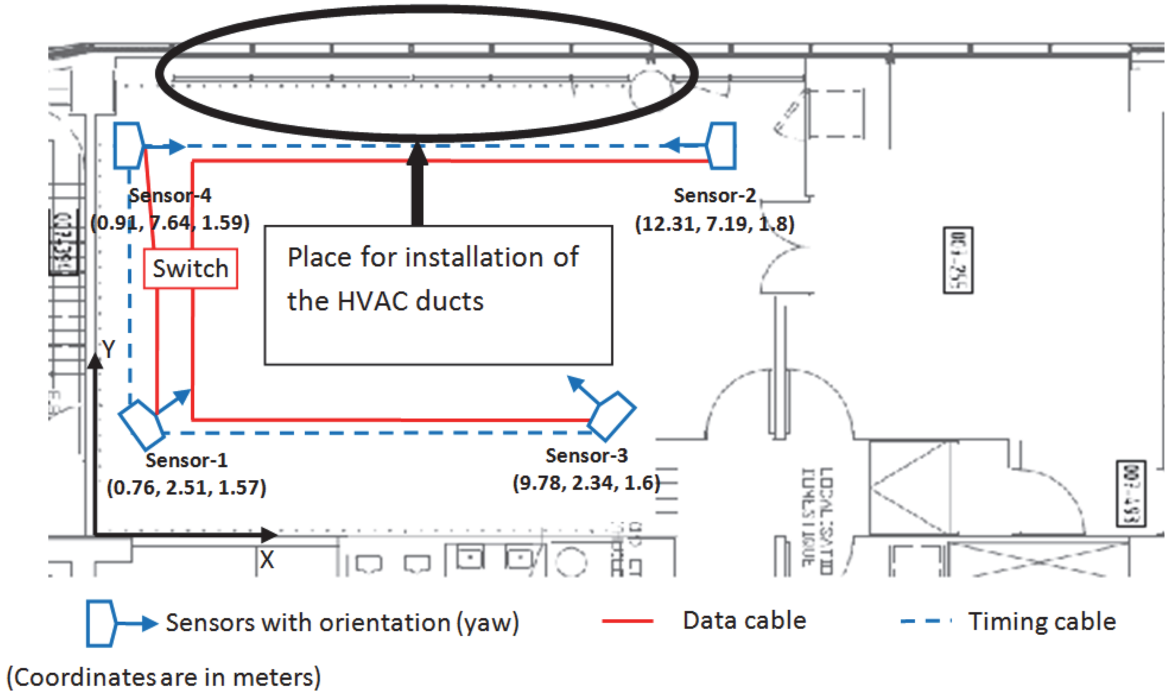


Figure 4-7 Floor Plan of the Construction Site and the Setting of the UWB System

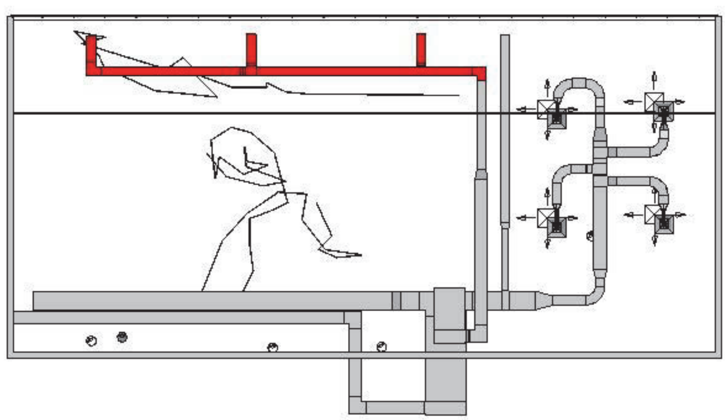


Figure 4-8 Floor Plan Generated in Revit Showing the Installed Ducts

Figure 4-9 shows the interface for selecting and loading the UWB data into the 3D model. It provides tag IDs and their coordinates at specific dates and times. The trace of each tag can be imported in Revit. The location, angle, and scale of traces can be adjusted through the interface as transformation should be applied on data captured from the UWB system to fit into the coordinate system of Revit.

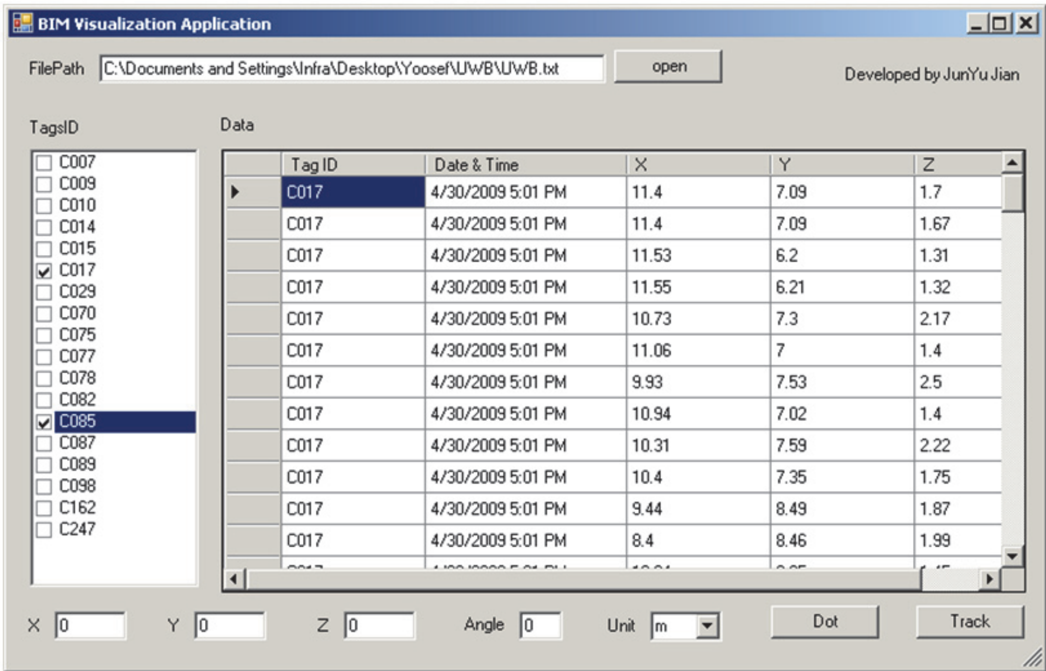


Figure 4-9 Revit Interface for Adding UWB Data

Figure 4-10 shows an AR view of the workers and their traces. Each of Traces shows the locations of a specific worker for a short duration. Figure 4-11 shows an example of augmenting the BIM model with a picture of the workers and their IDs. The IDs and their locations are extracted from the UWB data.

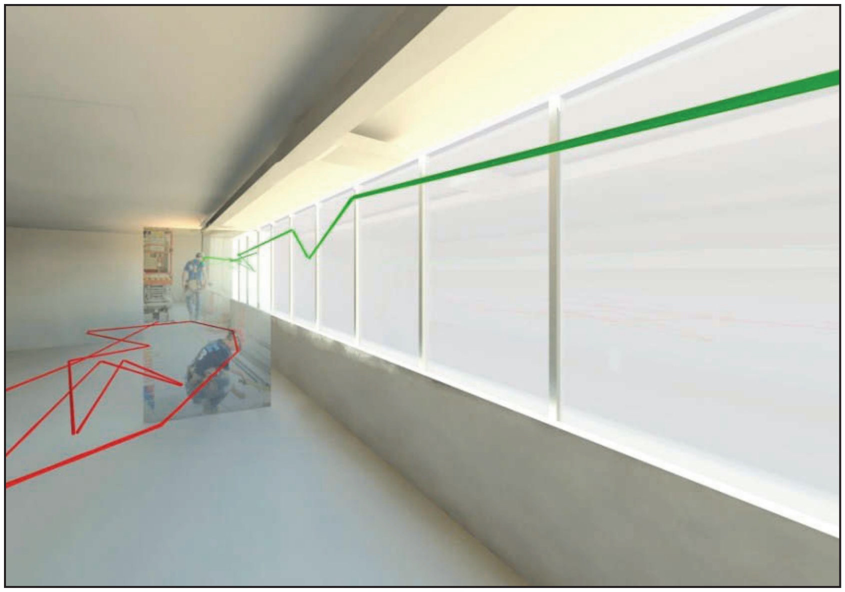


Figure 4-10 Augmenting the BIM Model with Picture of Workers and the Traces of Their Movement

Figure 4-11 Augmenting the BIM Model with Video of Workers and Their IDs

4.4 SUMMARY AND CONCLUSIONS

This research proposes a new approach based on AR to visually fuse the data from different sources including BIM, video monitoring, and an UWB RTLS. For this purpose, it is proposed to attach UWB tags to workers and equipment that need to be monitored on site. The proposed method can be used to better visualize construction and renovation operations and to retrieve information about the time, space and activities for construction and renovation projects. The potential benefits and the computational steps of this data integration have been discussed. Two case studies are used to show the feasibility of the proposed approach.

The conclusions of this research are: (1) A new approach has been presented based on AR to visually fuse the data from BIM, video, and UWB RTLS in order to better visualize and analyze construction and renovation operations; (2) The computational steps and the potential benefits of this data integration have been discussed; and (3) Two case studies have been used to demonstrate the feasibility of the proposed method. Further research is needed to fully develop and test the practical applications of the proposed method. In order to enhance the application of this method, APIs should be developed for BIM tools to use video cameras for AR-based construction and renovation operations visualization.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 SUMMARY OF RESEARCH

This research suggested using COBIE as a standard for FM required data handover at the commissioning phase. Moreover, the benefits of using BIM-based visualization in FM are studied. Different kinds of relationships between components and spaces (i.e. logical and physical) are defined. Moreover, cause-effect relationships between components and spaces are studied. The research proposed the integration of BIM, CMMS, and COBIE data for the visualization of facilities components in terms of deterioration condition and cause-effect relationships between components and space for visual analytics.

This research also proposes a new approach based on AR to visually fuse the data from different sources including BIM, video monitoring, and an UWB RTLS. For this purpose, it is proposed to attach UWB tags to workers and equipment that need to be monitored on site. The proposed method can be used to better visualize construction and renovation operations and to retrieve information about the time, space and activities for construction and renovation projects. Likewise, the potential benefits and the computational steps of this data integration have been discussed. The case studies demonstrated the practicality of the proposed approaches and proved the usability of the methods studied in this research.

5.2 CONCLUSIONS

The conclusions of the research about the *visual analytics in FM* are: (1) In order to have a comprehensive database for FM, it is necessary to integrate data from COBIE and CMMS with the BIM of the facility. The proposed methodology provides different methods for the integration of COBIE data with CMMS to create a comprehensive BIM database encompassing COBIE data and feeding CMMS and BIM tools. However, COBIE data should be required in the contracts to be provided to the owners by the contractors. It is impractical and inefficient to develop COBIE data in the commissioning phase; (2) The proposed visual analytics provides powerful tools for 3D and 4D visualization of the possible causes of problems in a building. To realize this method, this research first defines the spatial and logical relationships between components and spaces. Some of these relationships (i.e. spatial relationships) are already imbedded in the IFC model and can be mapped into relationships in a database; while other relationships (i.e. logical relationships) have to be added to the database; (3) It is important to define a set of queries in the relational database based on cause-effect relationships extracted from the literature and from FM domain experts. These queries use the spatial and logical relationships between components and spaces and will eventually form a knowledge base for visual analytics; and (4) The case study shows the feasibility of the proposed visual analytics method using available CMMS and BIM tools.

The conclusions of the research about the *augmented reality based visualization of construction and renovation operations* are: (1) A new approach has been presented based on AR to visually fuse the data from BIM, video, and UWB RTLS in order to better visualize and analyze construction and renovation operations; (2) The computational steps and the potential benefits of this data integration have been discussed; and (3) Two case studies have been used to demonstrate the feasibility of the proposed method.

5.3 LIMITATIONS AND FUTURE WORK

This research also identifies the limitations in terms of data and tool. IFC is under development and it does not encompass all the data related to the lifecycle of a facility. For the 4D simulation of the deterioration condition of the components, mapping the properties of components to their corresponding data is only applicable for some properties.

In the case study of visual analytics in FM, the building had not been commissioned completely and the FM department could not provide us with the COBIE data of the Genomics research center. The complete COBIE data could support the case study more comprehensively. The case study showed the need for more standardization of BIM and CMMS tools in addition to more development of BIM and IFC. Tools are needed to apply the defined relationships according to IFC standard. As BIM is not yet developed in its full shape, several inspection and maintenance related data need to be added to BIM for the full implementation of the proposed method.

The following work can be done to enhance the implementation of the proposed approach: (1) identify potential deterioration/failure cause-effect relationships and their spatial characteristics; (2) facilitate the implementation of COBIE in the commissioning phase of actual projects and to integrate the collected data with CMMS; (3) further develop BIM implementation plans for FM. New processes (the process re-engineering) that involve using BIM-based tools and COBIE standard together with CMMS can be explored. Moreover, challenges related to the adoption of these new tools and processes should be investigated; and (4) develop APIs in BIM tools to use video cameras for AR-based construction and renovation operations visualization.

REFERENCES

4D BIM (2011). Retrieved on April 2012, from: <http://en.wikipedia.org/wiki/4D_BIM>.

Abeid, J. and Arditi, D. (2002). Time-lapse digital photography applied to project management. Journal of Construction Engineering and Management, ASCE, Vol. 128, No. 6, pp. 530-535.

AIA, The American Institute of Architects (2007). Integrated project delivery: a guide. Retrieved on April 2012, from: <www.aia.org>.

Ahamed, S.S., Neelamkavil, J. and Canas, R. (2010). Impact of building information modeling on facility maintenance management, National Research Council Canada, Retrieved on April 2012, from: <www.nrc-cnrc.gc.ca/irc>.

Ahluwalia, S.S. (2008). A framework for efficient condition assessment of the building infrastructure, A thesis presented to the University of Waterloo in fulfillment of requirement for the degree of Doctor of Philosophy in Civil Engineering, Waterloo, Ontario, Canada, 2008.

Akcamete, A., Liu, X., Akinci, B. and Garrett, J.H. (2011). Integrating and visualizing maintenance and repair work orders in BIM: lessons learned from a prototype. Proceedings of the 11th International Conference on Construction Applications of Virtual Reality (CONVR), Weimar, Germany, pp. 639-649.

Akcamete, A., Akinci, B. and Garrett, J.H. (2010). Potential utilization of building information models for planning maintenance activities. Computing in Civil and Building Engineering, Proceedings of the 13th International Conference, W. TIZANI (Editor), 30 June-2 July, Nottingham, UK, Nottingham University Press, Paper 76, (8 pages, from CD).

Akcamete, A., Akinci, B. and Garrett, J.H. (2009). Motivation for computational support for updating Building Information Models (BIMs). Computing in Civil Engineering. pp. 523-532.

Anderson, R. (2010). An introduction to the IPD workflow for vectorworks BIM users, Nemetschek Vectorworks North America.

Autodesk (2011). Autodesk Revit Architecture, Retrieved on April 2012, from: <http://www.autodesk.com/revit-architecture/>.

Autodesk (2011). Autodesk Navisworks, Retrieved on April 2012, from: <http://www.autodesk.com/navisworks>.

Autodesk (2011). BIM and facilities management, Retrieved on April 2012, from: <http://www.autodesk.com/bim>.

Autodesk (2011). Tapping BIM using ODBC, Retrieved on April 2012, from: <http://www.autodesk.com/bim/>.

Becerik-Gerber, B., Jazizadeh, F., Li, N. and Calis, G. (2011). Applications areas and data requirements for BIM-enabled facilities management, Journal of construction engineering and management.

Becker, T., Nagel, C. and Kolbe, T.H. (2011). Integrated 3D modeling of multi-utility networks and their interdependencies for critical infrastructure analysis. Advances in 3D Geo-Information Sciences Lecture Notes in Geoinformation and Cartography. pp. 1-20

Behzadan, A.H., Timm, B.W. and Kamat, V.R. (2008). General-purpose modular hardware and software framework for mobile outdoor augmented reality applications in engineering. Advanced Engineering Informatics, Vol. 22, No.1, pp. 90-105.

Bjørkhaug, L., Bell, H., Krigsvoll, G. and Haagenrud, S.E. (2005). Providing life cycle planning services on IFC/IFD/IFG platform – a practical example, Proceedings of the 10th International Conference on Durability of Building Materials and Components, Lyon, France.

BuildingSMART (2011). International home of open BIM, Retrieved on April 2012, from: < http://www.buildingsmart.org>.

BuildingSMARTalliance (2011). A council of the National Institute of Building Sciences. Retrieved on April 2011, from: < http://www.buildingsmartalliance.com/>.

Buildingsmart-tech (2011). International home of open BIM, Retrieved on April 2012, from: < http://www.buildingsmart-tech.org>.

Chae, S. And Kano, N. (2007). Application of location information by stereo camera images to project progress monitoring, Proceedings of the 24th International Symposium on Automation & Robotics in Construction, ISARC, pp. 89-92.

Chae, S., and Yoshida, T. (2008). A study of safety management using working area information on construction site, Proceedings of the 25th International Symposium on Automation and Robotics in Construction, June 2008, Vilnius, Lithuania, pp. 292- 299.

Chen, H. M. and Wang, Y. H. (2009). A 3-dimentional visualized approach for maintenance and management of facilities, 26th international symposium on automation and robotics in construction (ISARC 2009), pp. 468-475.

Cho, Y.K., Youn, J.H. and Martinez, D. (2010). Error modeling for an untethered ultra-wideband system for construction indoor asset tracking. Automation in Construction, Vol. 19, pp. 43-54.

Dawood, N. and Mallasi, Z. (2006). Construction workspace planning: assignments and analysis utilizing 4D visualization technologies, Computer-Aided Civil and Infrastructure Engineering, Vol. 21, No. 7, pp. 498–513.

East, E. W. (2007). Construction operations building information exchange (COBIE): requirement definition and pilot implementation standard. ERDC/CERL TR-07-03, Contraction Engineering Research Laboratory, Champaign, IL.

East, E. W. and Nisbet, N. (2010). Analysis of life-cycle information exchange, Proceedings of the International Conference on Computing in Civil and Building Engineering, W. TIZANI (Editor), 30 June-2 July, Nottingham, UK, Nottingham University Press, (7 pages, from CD).

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors. second edition, Wiley, Hoboken, NJ.

El-Ammari, K., Hammad, A., Khabir, B. and Mozaffari, E. (2006). Integration and visualization issues in large-scale location-based facilities management systems, 6th International Conference on Construction Applications of Virtual Reality (CONVR 2006), Orlando, Florida, (10 pages, from CD).

FacilitiesNet (2008). BIM Software as a facility management tool, Retrieved on April 2012, from: <http://www.facilitiesnet.com/software/topic/>.

FMSystems (2011). Retrieved on April 2012, from: <http://www.fmsystems.com/>.

Ghavami, M., Michael, L.B. and Kohno, R. (2004). Ultra Wideband signals and systems in communication engineering, Wiley.

Giretti, A., Carbonari, A, Naticchia, B. and Grassi, M.D. (2009). Design and first development of an automated real-time safety management system for construction sites, Journal of Civil Engineering and Management, Vol. 15, No. 4, pp. 325-336.

Golparvar-Fard M., Pena-Mora, F. and Savarese, S. (2009). D4AR- a 4-demensional augmented reality model for automating construction progress monitoring data collection, processing and communication, Journal of information technology in construction, Vol. 14, pp. 129-153.

Hallberg, D. and Tarandi, V. (2011). On the use of open BIM and 4D visualisation in a predictive lifecycle management system for construction works, ITcon, Vol. 16, pp. 445-466.

Hammad, A., Garrett, J.H. and Karimi, H.A. (2002). Potential of mobile augmented reality for infrastructure field tasks. Proceedings of the applications of advanced technology in transportation conference (AATT' 2002), Cambridge, MA, pp. 456-472.

Hammad, A. and Motamedi, A. (2007). Framework for lifecycle status tracking and visualization of constructed facility components. Proceeding of the 7th International Conference on Construction Applications for Virtual Reality, October 23-24. Penn State University, University Park, PA, pp. 224-232.

Hammad, A., Wang, H. and Mudur, S.P. (2009). Distributed augmented reality for visualizing collaborative construction tasks, Journal of computing in civil engineering. Vol. 23, No. 6, pp. 418-427.

Hassanain, M. Froese, T. and Vanier, D. (2000). IFC-based data model for integrated maintenance management. 8th International Conference on Computing in Civil and Building Engineering (ICCCBE-VIII), Stanford University, California, USA, (9 pages, from CD).

Hegazy, T., Ahluwalia, S.S. and Attalla, M. (2010). Two condition indicators for building components based on reactive-maintenance data, Journal of Facilities Management, Vol. 8, Issue: 1, pp. 64-74.

IBC: Institute for BIM in Canada (2011). Environmental scan of BIM tools and standards. Retrieved on April 2012, from: <http://www.ibc-bim.ca/>.

IBM (2012). Smarter cities serious: understanding the IBM approach to efficient buildings. Retrieved on April 2012, from: <http://www.redbooks.ibm.com/redpapers/pdfs/redp4735.pdf>

Ifc-mBomb (2004). Ifc Model Based Operation and Maintenance of Buildings. Retrieved on April 2012, from: <http://buildingsmart.com/resources/viu-presentations/bath-viu-workshop/Ifc-mbomb_IAI_20ITM_20Bath_202004.pdf/view>.

IFMA (2011). International Facility Management Association. Retrieved April 2012, from: <www.ifma.org>.

Izkara J.L., Perez J., Basogain X. and Borro D. (2007). Mobile augmented reality, and advanced tool for the construction sector, Proceedings of the CIB 24th W78 Conference, Bringing ICT Knowledge to Work, Maribor, Slovenia, pp. 453-460.

Kaetzel L. J. and Clifton J. R. (1995). Expert/knowledge based system for materials in the construction industry: State-of-the-art report, Materials and Structures, Vol. 28, No. 177, pp. 160-174.

Khemlani L. (2004). The IFC building model: A look under the hood, AECbytes, Retrieved April 2012, from: <www.aecbytes.com/feature/2004/IFCmodel>.

Khosrowshahi F. and Banissi E. (2001). Visualisation of the degradation of building flooring systems, Proceedings of the 5th International Conference on Information Visualisation, IEEE Computer Society, pp. 507-514.

KIT, Karlsruhe Institute of Technology (2012). IfcViewer. Retrieved April 2012, from: <www.iai.fzk.de>.

Kyle, B. R., Vanier, D. J., Kosovac, B. and Froese, T. M. (2002). Visualizer: an interactive, graphical, decisions-support tool for service life prediction for asset managers, Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, pp. 1-9.

Liebich, T. (2009). IFC 2x Edition 3. Model Implementation Guide. Version 2.0. AEC3 Ltd. Retrieved on April, from: <http://www.iai-tech.org/>.

Linnert, C., Encarnacao, M., Stork, A. and Koch, V. (2000). Virtual building lifecycle – giving architects access to the future of buildings by visualizing lifecycle data. Proceedings of the 8th International Conference on Computing in Civil and Building Engineering, Stanford, California, USA, (8 pages, from CD).

Maximo (2011). Maximo Asset Management Software, Available from: <http://www-01.ibm.com/software/tivoli/products/maximo-asset-mgmt/>.

Microsoft (2012). Microsoft Access, Retrieved on April 2012, from: <http://www.microsoft.com/>.

Mitchell, J. and Schevers, H. (2005). Building Information Modeling for FM using IFC. Retrieved on April, from: <http://eprints.qut.edu.au/27188>

Motamedi, A. and Hammad, A. (2009). Lifecycle management of facilities components using Radio Frequency Identification and Building Information Model, Next Generation Construction IT, Journal of IT in Construction. Vol. 14, pp. 238-262.

Navon, R., and Sacks, R. (2007). Assessing Research Issues in Automated Project Performance Control (APPC). Automation in Construction. Vol.16, No. 4, pp. 474-484.

NBIMS (2007). National Building Information Modelling Standard Part-1: Overview, principles and methodologies, US national institute of building sciences facilities information council, BIM Committee, Retrieved April 2012, from: <http://www.facilityinformationcouncil.org/bim/publications.php>.

NIBS (2011). The National Institute of Building Sciences. Retrieved April 2012, from: <http://www.nibs.org/>.

Nisbe, N., (2010). BIMservices, command-line utilities for BIM, Retrieved April 2012, from: <http://www.aec3.com/>.

Pacific alliance technologies (2011). Setting up and adjusting the Revit camera, Retrieved April 2012, from: <http://ufolio.uoregon.edu/>.

PQDT (2012). ProQuest Dissertations & Theses, Retrieved on April, from: <http://0-search.proquest.com.mercury.concordia.ca/pqdtft?accountid=10246>.

Rad, H. N. and Khosrowshahi, F. (1997). Visualisation of Building Maintenance Through Time, Proceedings of IEEE Conference on Information Visualization, IEEE Computer Society, pp. 308-314.

Riaz, Z., Edwards, D.J., and Thorpe, A. (2006). Sightsafety: A hybrid information and communication technology system for reducing vehicle/pedestrian collisions, Automation in Construction, Vol. 15, pp. 719-728.

Rodriguez, S., Zhang, C., Motamedi, A. and Hammad, A. (2010). Location tracking of construction resources using UWB for better productivity and safety, International Conference on Computing in Civil and Building Engineering, 2010, London, UK.

Rundell R. (2006). How can BIM benefit facilities management?, AIA Cadalyst, Retrieved April 2012, from: <http://primeedge.com/asbuilt_news/BIM_FM.htm>.

Shahandashti, S.M., Rzavi, S.N., Soibelman, L., Berges, M., Caldas, C.H., Brilakis, I., Teizer, J., Vela, P.A., Haas, C., Garrett, J., Akinci, B. and Zhu, Z. (2011). Data fusion approaches and applications for construction engineering, Journal of Construction Engineering and Management, ASCE.

Singh H., Smith D. K. and Przybyla J. M. (2009). Reducing facility management costs through integration of COBIE and LEED – EB, JBIM.

Sjogren, J. and Kvarsvik, K. (2007). BuildingSMART Standars ―information and demonstration. EUREKABUILD Workshop, May, 2007.

Solibri (2012). Solibri Model Viewer. Retrieved April 2012, from: <www.solibri.com>.

Staub-French, S. and Khanzode, A. (2007). 3D and 4D modeling for design and construction coordination: Issues and lessons learned, ITCon, Vol. 12, pp. 381-407.

Steinberg, A.N. and Bowman, C.L. (2001). Revisions to JDL data fusion model, Handbook of multisensor data fusion, edited by Hall D.L. and Llinas J. CRC Press.

Teizer, J., Lao, D. and Sofer, M. (2007). Rapid automated monitoring of construction site activities using ultra-wideband. Proceedings of the 24th Int'l Symposium on Automation & Robotics in Construction, ISARC, Sept., 2007, India, pp. 23-28.

Uhlik, F. T. and Lores, G. V. (1998). Assessment of Constructability Practices among General Contractors. Journal of Architectural Engineering, Vol. 4, No. 3, pp. 113-123.

Underwood, J. and Isikdag, U. (2009). Handbook of research on building information modeling and construction informatics: concepts and technologies. Information science reference (an imprint of IGI global), PA.

Wang, X., Dou, W., Chen, S., Ribarsky, W. and Chang, R. (2010). An interactive visual analytics system for bridge management. Computer Graphics Forum, Vol. 29, No. 3), pp. 1033-1042.

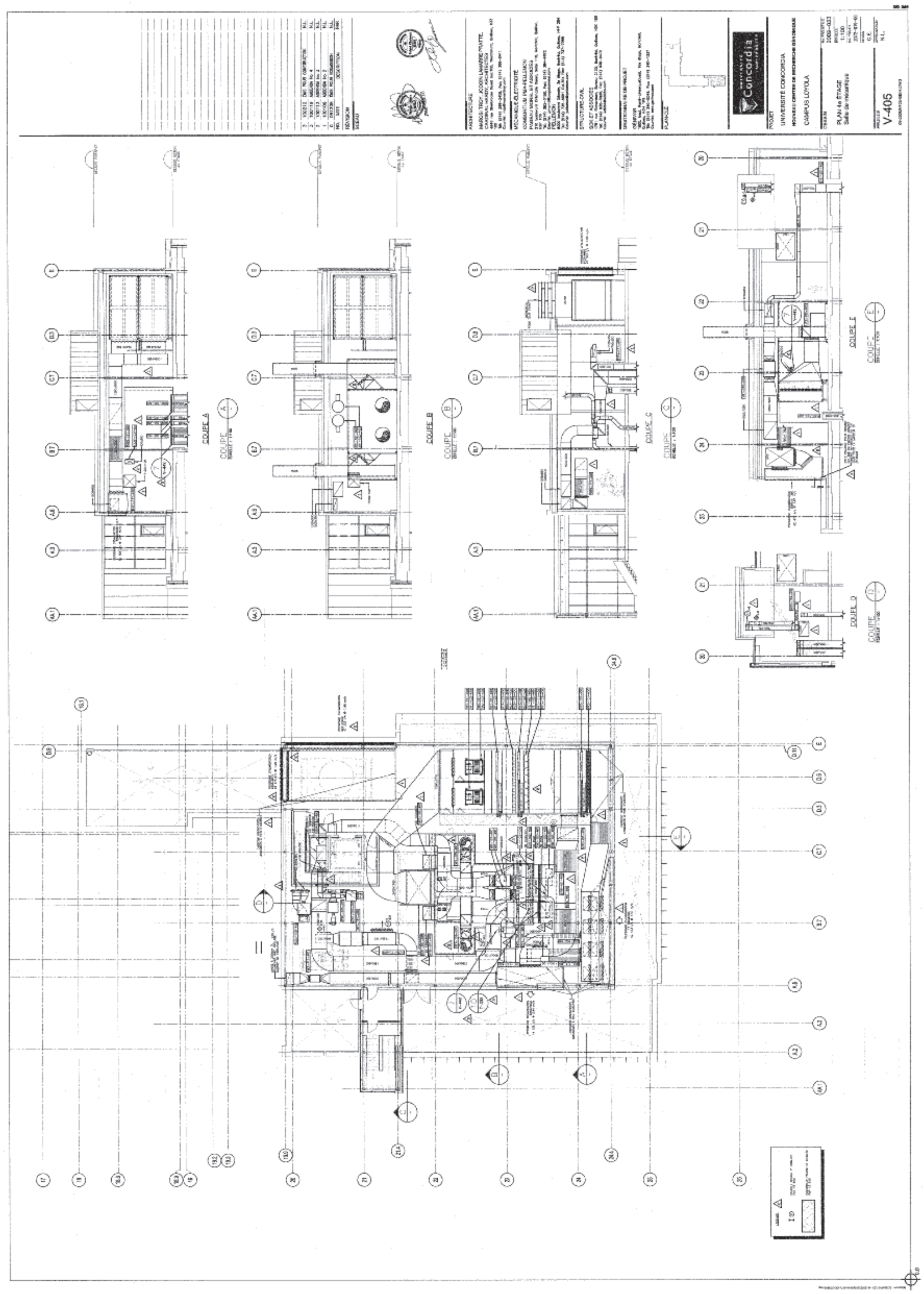
WBDG (2011). Whole Building Design Guide. Retrieved April 2012, from: <http://www.wbdg.org/>.

Wikipedia (2011). Angle of view, Retrieved April 2012, from: <http://www.wikipedia.org/>.

Wikipedia (2012). Structured Query Language (SQL), Retrieved April 2012, from: <http://www.wikipedia.org/>.

Zhang, C., AlBahnassi, H. and Hammad, A. (2010). Improving construction safety through real-time motion planning of cranes, Proceedings of the International Conference on Computing in Civil and Building Engineering, 2010, Birmingham, UK.

Appendix A – 2D Drawing of Genomics Research Center Mechanical Room



Appendix B – BIM Services

BIM Services is composed of some applications to manage and manipulate asset models and relate external formats to and from asset related data which COBIE2 would be an example of an external format. By using BIM Services tools, COBIE2 spreadsheet can be produced from an IFC file. The applications that could be done by using BIM Services include: Compliance1, Compare1, Report1, Filter1, and Transform1 which are explained as following (Nisbet, 2010):

Compliance1: to compare an asset model against expected data, regulatory, or client requirements.

Compare1: to compare two asset models.

Report1: to have some types of reports such as the report of the spatial hierarchy and contents, report on zones and the related spaces, report on types and their occurrence, and report on systems and their components.

Filter1: to remove specific chosen data from asset data or eliminating the unneeded geometry prior to transformations in order to decrease the size of the file.

Transform1: to transfer a BIM file to COBIE2 spreadsheet and vice versa.

Appendix C – COBIE

The owner's cost to have operations and maintenance manual in Portable Document Format (PDF) is shown in Figure C-1. This cost differs for simple and complex projects. For instance, for a simple project with \$80M construction cost, the cost of O&M manuals would be \$400K. However, for a complex project with the same amount of construction cost, the cost of O&M manuals is \$700K. Considering that most of these manuals are reproductions of construction submittal documents, the efficient information exchange process will decrease the cost. There are some costs associated with COBIE2 implementation. These costs include training, and in larger projects, the need for software (East and Nisbet, 2010).

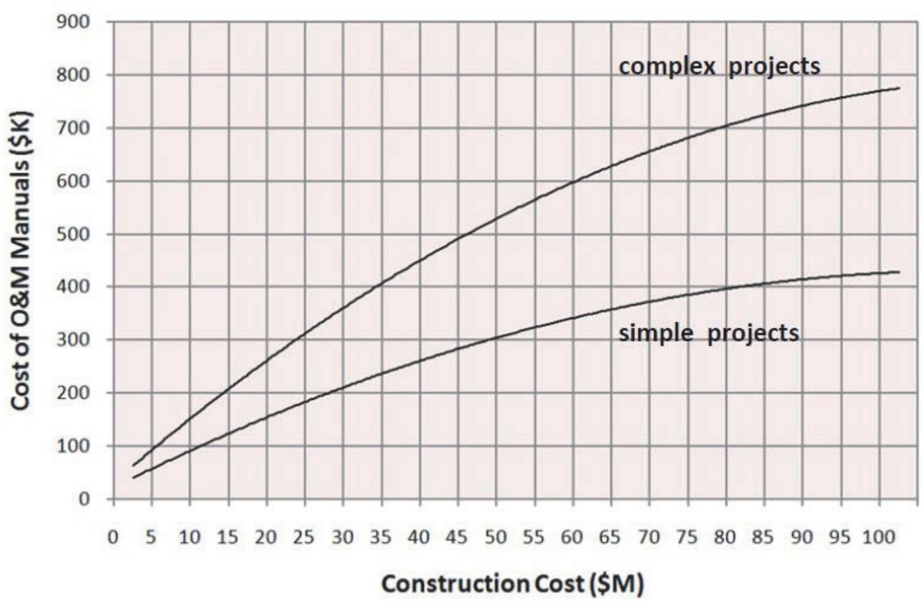


Figure C-1 Cost of Electronic O&M Documents (East and Nisbet, 2010)

IDM is used as the instruction to determine the required information exchange and components of the COBIE project. The IDM process defines three layers of information exchange specifications. The first layer is the definition of the business processes that need the exchange of information within a specific context. In the second layer, the general information exchange requirements that should happen at any stage of the business processes are defined. Finally, the third layer is the creation of the actual data format (functional parts) needed for technical information exchange among software vendors. The quality Assurance process is the initial effort that COBIE has focused on. The COBIE standard focuses on business processes that link together the contractor's supply chain management with the owner representative's quality assurance process. This process is about capturing information of the physical materials, products, and equipment which create a facility. These data and information about warranties and spare parts are the most important data which should be captured by COBIE (BuildingSMARTalliance, 2011).

FM Handover Aquarium is a project and aims to prove that the use of open standards is an enabler for the intended process integration (WBDG, 2011). The vendors should prove that their software meet portion of the IFC model needed to support FM which is defined by FM handover MVD. The certification is issued by the international buildingSMART. The firm which provides a FM handover MVD should indicate that their FM handover MVD has been implemented in IFC format and meets the format and quality requirements. Certifications are issued for both producers and consumers of FM handover information (buildingsmart-tech, 2011).

Figure C-2 shows an example of component worksheet in which each column has a specific color. All worksheets share the same or similar column headings and color coding. In Figure C-2, equipment schedule is related to the design phase, and the installed equipment is related to construction phase. The first column always should be a unique name with no commas. Yellow color is for required values and orange color references other worksheets. For example, space names found in the "Name" column of the "space" worksheet. Purple color shows external system data. Purple lists map the IFC model and may not be changed. Green color is optional (WBDG, 2011).

	A	B	C	D	E	F	G	H	I	J	K
1	Name	CreatedBy	CreatedOn	TypeName	SpaceNames	Description	ExtSystem	ExtObject	ExtIdentifier	SerialNumber	InstallationDate
2	Door-100A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100A	Door Type D1		IfcDoor		000-01-1	1-Mar-200
3	Door-100F	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100B	Door Type D1		IfcDoor		000-01-2	1-Mar-200
4	Door-100G	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100A	Door Type D1		IfcDoor		000-01-3	1-Mar-200
5	Door-101A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100A	Door Type D1		IfcDoor		000-01-4	1-Mar-200
6	Door-101A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	101	Door Type D1		IfcDoor		000-01-4	1-Mar-200
7	Door-102A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100B	Door Type D1		IfcDoor		000-01-5	1-Mar-200
8	Door-102A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	102	Door Type D1		IfcDoor		000-01-5	1-Mar-200
9	Door-103A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100A	Door Type D1		IfcDoor		000-01-6	1-Mar-200
10	Door-104A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100A	Door Type D1		IfcDoor		000-01-7	1-Mar-200
11	Door-104A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	104	Door Type D1		IfcDoor		000-01-7	1-Mar-200
12	Door-105A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	100A	Door Type D1		IfcDoor		000-01-8	1-Mar-200
13	Door-105A	bjerold@je.com	2009-08-13T16:06:53	Hardware items	105	Door Type D1		IfcDoor		000-01-8	1-Mar-200
14	Door-100C	bjerold@je.com	2009-08-13T16:06:53	Overhead Coiling Doors Assembly	100A	Overhead Door		IfcDoor		C600-012-01	1-Mar-200
15	Door-100D	bjerold@je.com	2009-08-13T16:06:53	Overhead Coiling Doors Assembly	100A	Overhead Door		IfcDoor		C600-012-02	1-Mar-200
16	Door-100E	bjerold@je.com	2009-08-13T16:06:53	Overhead Coiling Doors Assembly	100A	Overhead Door		IfcDoor		C600-012-03	1-Mar-200
17	Door-100B	bjerold@je.com	2009-08-13T16:06:53	Overhead Coiling Doors Assembly	100A	Overhead Door		IfcDoor		C600-012-04	1-Mar-200
18	HP-1	bjerold@je.com	2009-08-13T16:06:53	HVAC System Components and Equipment	100A	Heat Pump		objComponent		1000-00-1	1-Mar-200
19	RH-1	bjerold@je.com	2009-08-13T16:06:53	HVAC System Components and Equipment	100A	Radiant Heater		objComponent		236S-300-1	1-Mar-200
20	RH-2	bjerold@je.com	2009-08-13T16:06:53	HVAC System Components and Equipment	100A	Radiant Heater		objComponent		236S-300-2	1-Mar-200
21	RH-3	bjerold@je.com	2009-08-13T16:06:53	HVAC System Components and Equipment	100A	Radiant Heater		objComponent		226S-200-1	1-Mar-200

Instruction / Contact / Facility / Floor / Space / Zone / Type / **Component** / System / Spare / Resource / Job / Document / Attribute / Coordinate / Conne

Figure C-2 Component Worksheet (WBDG, 2011)

Some project practitioners are reluctant to use the improved COBIE information exchange method as the economic benefits of using such a new method have not convinced them yet. Legal issues and software have decreased the probability of adoption of new open standards (East and Nisbet, 2010). The benefits of applying COBIE and the comparison between current status of practice for data handover and COBIE assisted scenario are studied by East and Nisbet (2010). They have implemented a cost model called COBIE2 calculator which enables the mangers to compare the traditional approach for information exchange process with the use of the open data standards for information exchange.

For the implementation of this model, first, the required or most commonly used information which is produced during the facility delivery period and is useful for the O&M phase, has been identified. Then, the documentation processes of these data in addition to identification of overall factors affecting those processes, is done. The indirect costs arising from the affected processes have been captured. Then all the definitions have been validated through interviews with some experts and practitioners. The direct cost of information discovery, changing the format, distribution, and production of paper documents is explicitly included in the traditional information exchange model.

Table C-1 shows an example of the comparison of the tasks required to produce the commissioning agent's "Installed Equipment List" deliverables, between traditional paper-based and COBIE2 approach (East and Nisbet, 2010).

Table C-1 Tasks to Complete the Installed Equipment List (by Process) (East and Nisbet, 2010)

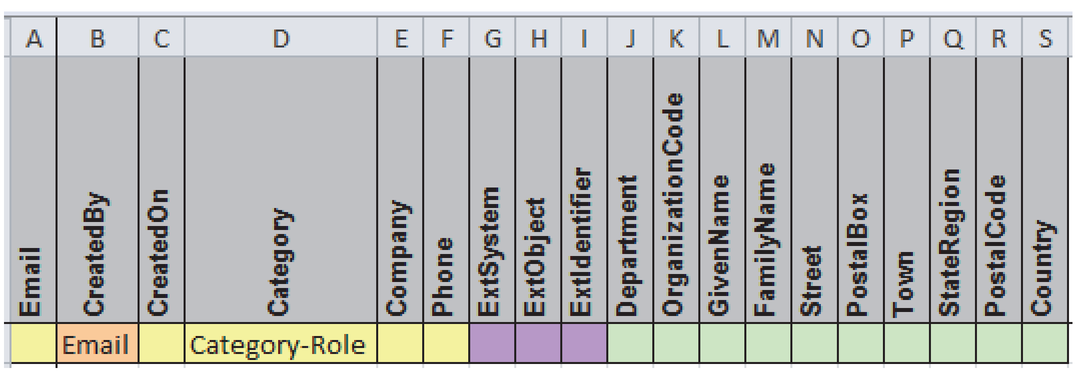
Task	**Process Used**	
	Traditional	**COBIE2**
Document equipment as installed	-	Yes
Extract equipment list from drawings	Yes	
Conduct site survey to identify serial numbers	Yes	
Compile site survey notes into equipment list	Yes	
Review & update equipment list	Yes	Yes
Reproduce and publish site survey document	Yes	-
Post COBIE2 w/update equipment to server	-	Yes

Table C-2 demonstrates the cost savings resulting from the information-centric COBIE2 process versus the traditional approach which is document based. Application of COBIE2 eliminates the paper duplication, routing, handling, processing, and archiving. There is a perception that the use of BIM only has benefits for the owner, but the result of this study shows that it has a large benefit to the construction contractor (East and Nisbet, 2010).

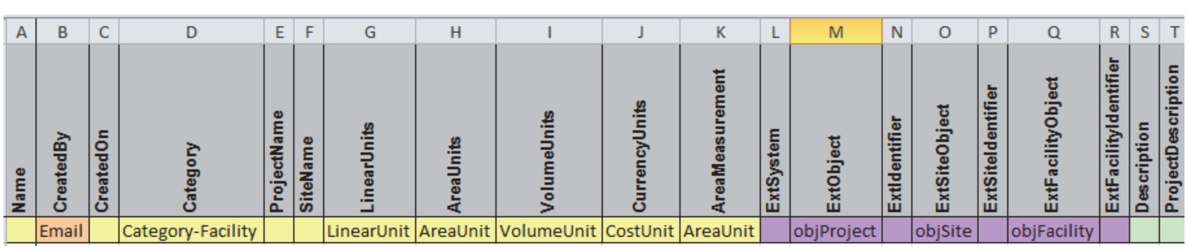
Table C-2 Document-Centric vs. Information-Centric Approaches (East and Nisbet, 2010)

Activity	Estimated cost		Estimated COBIE2 savings		
	Traditional	COBIE2	Total	Per sq meter	% project cost
Construction submittal processing	$39,000	$11,600	$27,400	$6.09	0.25%
Production of equipment lists	$21,000	$7,900	$13,100	$2.91	0.12%

Figure C-3 shows the sixteen worksheets of COBIE2 in detail.



Contact



Facility

A	B	C	D	E	F	G	H	I	J
Name	CreatedBy	CreatedOn	Category	ExtSystem	ExtObject	ExtIdentifier	Description	Elevation	Height
	Email		FloorType		objFloor				

Floor

A	B	C	D	E	F	G	H	I	J	K	L	M
Name	CreatedBy	CreatedOn	Category	FloorName	Description	ExtSystem	ExtObject	ExtIdentifier	RoomTag	UsableHeight	GrossArea	NetArea
	Email		Category-Space	Name			objSpace					

Space

A	B	C	D	E	F	G	H	I
Name	CreatedBy	CreatedOn	Category	SpaceNames	ExtSystem	ExtObject	ExtIdentifier	Description
	Email		ZoneType			objZone		

Zone

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
Name	CreatedBy	CreatedOn	Category	Description	AssetType	Manufacturer	ModelNumber	WarrantyGuarantorParts	WarrantyDurationParts	WarrantyGuarantorLabor	WarrantyDurationLabor	WarrantyDurationUnit	ExtSystem	ExtObject	ExtIdentifier	ReplacementCost	ExpectedLife	DurationUnit
	Email		Category-Product		AssetType	Email		Email		Email		DurationUnit		objType				DurationUnit

Type

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Name	CreatedBy	CreatedOn	TypeName	Space	Description	ExtSystem	ExtObject	ExtIdentifier	SerialNumber	InstallationDate	WarrantyStartDate	TagNumber	BarCode	AssetIdentifier
	Email		Name	Name			objComponent							

Component

A	B	C	D	E	F	G	H	I
Name	CreatedBy	CreatedOn	Category	ComponentNames	ExtSystem	ExtObject	ExtIdentifier	Description
	Email		Category-Element			objSystem		

System

A	B	C	D	E	F	G	H	I	J	K	L
Name	CreatedBy	CreatedOn	Category	TypeName	Suppliers	ExtSystem	ExtObject	ExtIdentifier	Description	SetNumber	PartNumber
	Email		SpareType	Name	Email		objSpare				

Spare

A	B	C	D	E	F	G	H
Name	CreatedBy	CreatedOn	Category	ExtSystem	ExtObject	ExtIdentifier	Description
	Email		ResourceType		objResource		

Resource

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
Name	CreatedBy	CreatedOn	Category	Status	TypeName	Description	Duration	DurationUnit	Start	TaskStartUnit	Frequency	FrequencyUnit	ExtSystem	ExtObject	ExtIdentifier	TaskNumber	Priors	ResourceNames
	Email		JobType	JobStatusType	Name			DurationUnit		DurationUnit		DurationUnit		objJob				

Job

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Name	CreatedBy	CreatedOn	Category	ApprovalBy	Stage	SheetName	RowName	Directory	File	ExtSystem	ExtObject	ExtIdentifier	Description	Reference
	Email		DocumentType	ApprovalBy	StageType	SheetType					objDocument			

Document

A	B	C	D	E	F	G	H	I	J	K	L
Name	CreatedBy	CreatedOn	Category	SheetName	RowName	Value	Unit	ExtSystem	ExtObject	ExtIdentifier	Description
	Email		StageType	SheetType					objAttribute		

Attribute

A	B	C	D	E	F	G	H	I	J	K	L
Name	CreatedBy	CreatedOn	CoordinateType	SheetName	RowName	CoordinateXAxis	CoordinateYAxis	CoordinateZAxis	ExtSystem	ExtObject	ExtIdentifier

Coordinate

A	B	C	D	E	F	G	H	I	J
Name	CreatedBy	CreatedOn	ComponentName1	ComponentName2	ConnectionType	ExtSystem	ExtObject	ExtIdentifier	Description

Connection

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Name	CreatedBy	CreatedOn	Type	Risk	Chance	Impact	SheetName1	RowName1	SheetName2	RowName2	Description	Owner	Mitigation	ExtSystem	ExtObject	ExtIdentifier

Issue

Figure C-3 the Sixteen Worksheets of COBIE2

APPENDIX D – INVENTORY OF SOME AIR CONDITIONING AND REFRIGERATION EQUIPMENT OF GENOMICS RESEARCH CENTER

Table D-1 shows the data related to the refrigerants used in the Genomics research center

Table D-1 Refrigerants Used in the Genomics Research Center

Description	Genomics research center	
	#1	#2,3,4
Local	400	S100-12
Marque	Carrier	Engineered Air
Model	RB36B398A5751CC	MD60W-Y
Capacity (Tonnes)	500	60
Type of réfrigérant	HFC-134A	R410A
Quantity of réfrigérant (Lbs)	1518	
Valeur Budgétaire 2011	$150 000	$270 000 pour les 3

APPENDIX E - LIST OF RELATED PUBLICATIONS

Asen, Y., Motamedi, A. and Hammad, A. (2012). BIM-based visual analytics approach for Facilities Management. Proceedings of the 14th International Conference on Computing in Civil and Building Engineering (ICCCBE 2012), Moscow, Russia.

Hammad, A., Asen, Y. and Zhang, C. (2011). Visualizing construction prococess using augmented reality: fusing BIM, video monitoring and location information. Proceedings of the 11th International Conference on Construction Applications of Virtual Reality (CONVR 2011), Weimar, Germany.

Zhang, C., Hammad, A., Setayeshgar, S. And Asen, Y. (2012). Automatic generation of dynamic virtual fences as part of BIM-based prevention program for construction safety. Proceedings of the 2012 Winter Simulation Conference, Berlin, Germany.